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DEVELOPMENT OF A COMPUTER PROGRAM FOR DETERMINATION OF SEARCH AREAS FOR SEACH AND RESCUE OPERATIONS OF THE UNITED STATES COAST GUARD

DAVID F. CUNNINGHAM
and
DONALD L. FRANTZ

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DEVELOPMENT OF A COMPUTER PROGRAM FOR DETERMINATION OF SEARCH AREAS FOR SEARCH AND RESCUE OPERATIONS OF THE UNITED STATES COAST GUARD

by

David F. Cunningham

Lieutenant, United States Coast Guard

and

Donald L. Frantz

Lieutenant Commander, United States Coast Guard

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
MANAGEMENT

United States Naval Postgraduate School
Monterey, California

1965

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This work is accepted as fulfilling
the research paper requirements for the degree of
MASTER OF SCIENCE
IN
MANAGEMENT
from the
United States Naval Postgraduate School

ABSTRACT

The increase in trans-oceanic travel and maritime operations have created a need for new and improved search and rescue techniques and facilities. This study briefly describes the various phases of search and rescue operations and reviews the doctrine currently used by this Nation as set forth in the National Search and Rescue Manual.

Attention is then directed to developing a computer program which utilizes current doctrine in the solution of one portion of the search and rescue problem. The program determines the most probable location of survivors (datum) and the associated search areas at any specified time for an off-shore distress case with an estimated reported distress incident position. The resulting program, written in Fortran 60, is included with sample test data.

Finally, recent developments in computer-generated informations systems which may offer improvements in the existing doctrine are discussed.

TABLE OF CONTENTS

CHAPTER PAGE

I. STATEMENT OF THE PROBLEM........ 1

Theoretical Background........ 2

Statement of Special Purpose........ 4

The Problem........ 5

Definitions of Key Terms........ 6

Distress phase........ 6

Distressed unit........ 6

Rescue Coordination Center........ 6

On-Scene Commander........ 7

Search unit........ 7

Distress incident position........ 7

Datum........ 8

Search Area........ 8

Search radius........ 8

Total probable error of position........ 9

Initial position error........ 9

Navigation error of the search unit........ 9

Life raft drift error........ 10

Drift........ 10

Drift (max)........ 10

Drift (min)........ 10

CHAPTER PAGE

Local wind current. 12

Leeway. 13

Parachute drift. 13

Assumptions. 13

Limitations. 14

Research Significance. 15

II. REVIEW OF THE LITERATURE. 17

Doctrine on the Determination of the Search Area According to the National Search and Rescue Manual. . 18

Studies Dealing with Parachute Drift and Ocean Current Drift. 32

Parachute drift. 32

Ocean current drift. 35

Note on Additional Literature Relating to the Overall Search and Rescue Problem. 38

III. THE STUDY. 40

Method. 40

Procedure. 40

Determination of datum at any specified time. 42

Leeway. 45

Local wind current. 48

Average sea current. 49

Resultant total drift. 49

CHAPTER PAGE

Determination of total probable error of position....... 54

Initial position error of the distress incident........ 55

Navigational error of the search unit............... 59

Drift error.................................... 61

Determination of the limits of the search area......... 61

IV. RESULTS.. 70

Trial Data Computations................................ 72

V. SUMMARY AND CONCLUSIONS........................... 76

Summary.. 76

Conclusions.. 76

Implications... 79

Recommendations of Areas for Further Study........... 80

Determination of a datum and associated search area when the time of the incident and estimated position are not known........................ 80

Development of a fully operational free fall and parachute drift program........................ 80

Development of a program to handle small craft (inshore) distress cases......................... 81

Development of a program relating search area, search units, and search patterns................. 81

Studies evaluating the frequency of distress cases and the location of SAR facilities................ 82

Continued drift analysis.............................. 82

BIBLIOGRAPHY.. 84

APPENDIX A. Flowchart Symbols and Definitions............... 89

APPENDIX B. Program SAR. 91

APPENDIX C. "Parachute Drift". 115

APPENDIX D. Extracts from the Study: "Free Fall and Parachute Drift". 156

APPENDIX E. "Computer Produced Synoptic Analyses of Surface Currents and Their Application for Navigation. 174

APPENDIX F. Surface Drift Ellipse Program. 188

LIST OF FIGURES

FIGURE PAGE

1. Components of Drift, D, When Fluctuations are Small or Existing Conditions are known with a High Degree of Accuracy. 11

2. A Minimax Plot of Drift Components when Fluctuations are Large or Uncertainty Exists as to the Exact Conditions ar the Scene. 11

3. Graphical Solution of Drift Error (Minmax). 26

4. Repeated Expansion Search Areas for Stationary Datum Point. 31

5. Repeated Expansion Search Areas for Moving Datum Point. . 31

6. The Basic Process of Determining the Search Area. 41

7-A. The Factors Associated with the Forecasted Datum. 43

7-B. Flow Diagram for Determining Leeway Drift Components. . . 47

7-C. Flow Diagram for Determining Local Wind Current Drift Component. 50

7-D. Flow Diagram for Determining the Average Sea Current Drift Component. 51

7-E. Flow Diagram Combining Drift Vectors and Datum$_{t_0}$ Yielding Forecasted Datum$_{t_1}$. 51

8. Complete Drift Picture for Life Raft. 52

9. Complete Drift Picture for Life Boat. 52

10-A. Components of Total Probable Error of Position. 54

10-B. Flow Diagram for the Determination of the Initial Position Error, X. 57

10-C. Flow Diagram for the Determination of the Navigational Error of the Search Unit, Y. 60

10-D. Flow Diagram for the Determination of Drift Error, d_e. 62

FIGURE PAGE

10-E. Flow Diagram for the Final Determination of Total Probable Error of Position, c........................... 63

11. Flow Diagram for the Determination of the Search Area..... 64

12. General Flow Diagram for Equivalent Temperatures at Various Wind Velocities............................ 67

13. Flow Diagram for Immersion Hypothermia................. 69

CHAPTER I

STATEMENT OF THE PROBLEM

Man's continuing struggle against the elements at sea is noted throughout history. In the Book of Psalms it is recorded:

> They that go down to the sea in ships, that do business in great waters;
> These see the works of the LORD, and his wonders in the deep.
> For he commandeth, and raiseth the storm wind, which lifteth up the waves thereof.
> They mount up to the heaven, they go down again to the depths: their soul is melted because of trouble.
> They reel to and fro, and stagger like a drunken man, and are at their wit's end.[1]

Each year literally thousands of people find themselves in distress while located upon the high seas or upon waters over which the United States has jurisdiction. Fortunately for most of them, their rescue is only a matter of waiting a relatively short time. This life-saving assistance usually appears in the form of one or more units operated by the United States Coast Guard. Specifically charged by Title 14, United States Code,[2] the United States Coast Guard carries the responsibility of establishing, operating and maintaining these facilities

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[1] The Holy Bible (King James Version; Cleveland: The World Publishing Company, n.d.), Psalms 107:23-27.

[2] United States Code, Title 14 (Coast Guard Chapter 1, Section 2, Vol. III, (1958 edition); Washington: Government Printing Office, 1959), p. 2286.

necessary to provide such assistance as may be required by any person or persons, vessels or aircraft in distress upon these waters.

I. THEORETICAL BACKGROUND

The task of successfully conducting search and rescue operations at sea has been a challenge ever since man first ventured out upon the hydrosphere. Modern technology has contributed greatly to providing the answer to this challenge. Nevertheless, each individual case presents the would-be-rescuers with many complex problems faught with uncertainties and the capriciousness of Nature.

To increase man's effectiveness in rendering assistance to his fellow man on the high seas, the martime nations of the world have combined their efforts in developing and improving search and rescue techniques, establishing necessary communication systems, and providing for mutual assistance and cooperation in large scale operations. The National Search and Rescue Manual, CG-308, developed by the United States Coast Guard, serves as this Nation's leading guide in this area.[3]

[3] United States Coast Guard, National Search and Rescue Manual, CG-308 (Washington: Government Printing Office, 1959, Amended 1964).

Generally, search and rescue operations can be divided into four main phases. The first of these is the "Alert" when a distress or potential distress situation is suspected. This would occur, for example, when an aircraft or boat is overdue or has failed to meet routine scheduled communications checks. During this phase efforts are directed to determine if, in fact, there is an overdue craft, and whether or not communications can be established with the craft in question.

The second, the "Distress" phase, follows when the "Alert" fails to establish the fact that a distress does not exist. Here one finds efforts being directed to determine the most likely location of the distressed unit with an associated area for searching and the assignment and dispatching of search units to the scene of the search.

The third is the "Search" phase wherein those search units previously designated conduct searches of the area determined in the second phase.

The fourth and last phase is the "Rescue" which hopefully follows a successful "Search."

It is evident when a distress incident does exist that no amount of searching will lead to rescue if this searching has been conducted in an area which does not contain the unit in distress. Therefore, it is essential that the second phase produce sound information and directions for the search units. This requires the careful analysis and evaluation of

many complex and interrelated factors. Some of these factors are the nature of the distress, reliability of navigational information available on the probable position of the distressed unit, the effects of ocean currents, local wind-driven currents, sea and swell conditions, life raft drift or leeway, possible effect of parachute drift if such is present in the distress incident under consideration, estimated time of survival under conditions existing at the scene, time involved for the search units to reach the scene with the associated change in site location caused by the factors stated earlier, the navigational errors of the search units, and the various probabilities associated with detection in different size areas.

At the present time the evaluation and analysis of these factors are carried out by human decision-makers with the aid of excellent guidelines, charts, graphs and tables. The final decision is, therefore, a human one which requires time to develop, possesses inherent chances for error in the calculations, and, by its very nature, must be subject to the human bias and judgement of the decision-maker which may or may not adversely effect the decision.

II. STATEMENT OF SPECIAL PURPOSE

The advent of the computer has greatly facilitated scientific analysis and routine decision-making. To date the computer has not been applied

to the search and rescue problem although the idea has been expressed and has been the subject of some feasibility studies. The application of computers in this field should greatly facilitate the analysis of the many factors involved and also reduce the time required to reach a decision. In view of the fact that human lives are at stake in these operations, it is mandatory that the best possible decisions be made with the information and alternatives available, and these decisions must be made in the shortest possible time. The following problem has been selected with these thoughts in mind.

III. THE PROBLEM

It is the purpose of this study (1) to completely develop a computer flow diagram and associated computer program using the Control Data Corporation compiler Fortran 60 language (equivalent to Fortran II) for that portion of the "Distress" phase of search and rescue (SAR) operations relating to the determination of a datum point and associated search area based on the doctrine outlined in the National Search and Rescue Manual, Chapter Six; and (2) to investigate the possible development of those programs encountered during the research process which appear to offer improved techniques for analyzing and evaluating various portions of the problems encountered in the "Distress" phase. These potentially improved techniques will be submitted to the United States Coast Guard for evaluation.

IV. DEFINITIONS OF KEY TERMS

The major key term under consideration is the "Distress" phase. As used in Chapter Six of the National Search and Rescue Manual this refers to that phase of search and rescue operations wherein the estimated location of the distress incident and an associated surrounding area called the "search area" are determined and designated for any specified time. It also includes the assignment and dispatching of search units to the scene of the distress incident. However, for the purpose of this study no consideration will be given to the assignment and dispatching of search units.

The following terms directly associated with the "Distress" phase will be used:

Distressed unit. The distressed unit is that craft whose survivors require rescue or assistance.

The object of the search may consist of a disabled vessel of any type, a downed aircraft, a life raft or life boat, or any form of survival equipment which will support a survivor or survivors on the water's surface, or, in some cases, the bodies of those who did not survive but which may be floating.

Rescue Coordination Center. The Rescue Coordination Center (RCC) is that operational office responsible for the initiation, coordination and

overall control of search and rescue operations for the specific areas under its jurisdiction. For Pacific operations this is controlled by Commander, Western Area, and for Atlantic operations it is controlled by Commander, Eastern Area. The specific individual responsible for the various decisions required on any given distress case is referred to as the RCC Controller.

On-Scene Commander. This is the commander of a search unit at or near the scene of the search who has been designated by the RCC Controller as the commander responsible for controlling and coordinating the efforts of the various units participating in the search while they are operating at the scene.

Search unit. Any unit which is actively participating in the search while under some form of control of the Rescue Coordination Center (RCC) or On-Scene Commander (OSC) is designated as a search unit. This may be an aircraft or surface vessel, commerical or military.

Distress incident position. This is the geographical position of the distressed unit at the time that the distress ocurred. The accuracy with which this position is determined will depend upon the specific nature of the distress and the time and facilities available for determining the position.

Datum. The datum point is that geographical position which represents the most likely location of the survivors at any specified time. Generally, the initial datum will correspond with the "distress incident position." At any time after the distress has occurred, the datum point will have moved in response to the forces of Nature and the efforts of the survivors. The datum point is considered to be in the center of any designated search area. It serves as a reference point for determining the limits of a designated search area.

Search area. That area in which the survivors are believed to be located and which can be covered with a reasonable degree of thoroughness by the search units is defined as the search area. It is bounded by limits established by the search radius which extends outward from the datum point.

Search radius. The search radius, (R), is the distance (in nautical miles) from the datum point to the edge of the search area. It is a function of the number of the search, for example--the second search, and the total probable error of position. The number of the search determines the safety factor to be applied. The total probable error of position is a function of several other factors which are defined below. In general, if the search radius is R, the safety factor is SF, and total probable error of position is c, then

$$R = SF \times c$$

Total probable error of position. The total probable error of position, (c), is that distance (in nautical miles) which represents the best estimate of position error when the following factors are taken into consideration:

a. Initial position error of the distressed unit, (X).

b. Navigational error of the search unit(s), (Y).

c. Life raft drift error, (d_e).

Total probable error of position is a scalar quantity which is applied to vectors extending in all directions from the datum point. It is represented by the equation:

$$c = \sqrt{d_e^2 + X^2 + Y^2}$$

A review of the development of this equation is contained in Chapter II.

Initial position error, (X). This is an estimate of the distance (in nautical miles) by which the distress incident position may be in error. It is a function of the method of navigation used to fix the position of the distressed craft.

Navigational error of the search unit, (Y). The navigation used in guiding the search units to the distress incident position or datum point and throughout the conduction of the search will be subject to varying degrees of error depending upon the method of navigation used. This error (in nautical miles) must be considered when determining the total probable error of position, c, and the resulting search radius.

Life raft drift error, (d_e). Once survivors are free of the distressed unit and floating upon the surface, they will be subjected to both surface currents and surface winds. The interaction of these forces, the nature of the survival craft--that is, whether it is a life raft, life boat or life jacket--and the time span over which they react, all contribute to a resultant drift vector, D. This drift vector may have maximum and minimum values depending upon the variations in the forces of Nature during the period of interaction and the availability of accurate information about the weather conditions at the scene of the distress incident. This variation introduces the concept of life raft drift error, (d_e), which will contribute to the total probable error of position.

Drift. The movement of the survivors (datum) upon the surface is represented by the vector, D. This is the vector which is the sum of the average sea current vector, the local wind current vector, and the leeway vector. Although the average sea current is assumed to have a constant value, the latter two vectors may vary thus contributing to maximum and minimum values for drift, D.

Drift (max). Drift (max), D_{max}, is that vector which represents the greatest displacement possible for a given datum during a specified period of time, Δt.

Drift (min). Drift (min), D_{min}, is that vector which represents the minimum displacement possible for a given datum during a specified period of time, Δt.

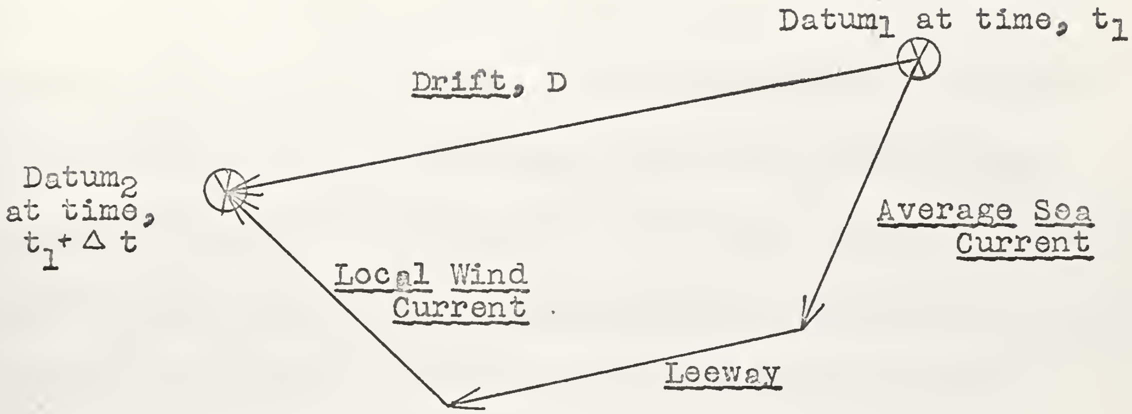

FIGURE 1

COMPONENTS OF DRIFT, D, WHEN FLUCTUATIONS ARE SMALL OR EXISTING CONDITIONS ARE KNOWN WITH A HIGH DEGREE OF ACCURACY

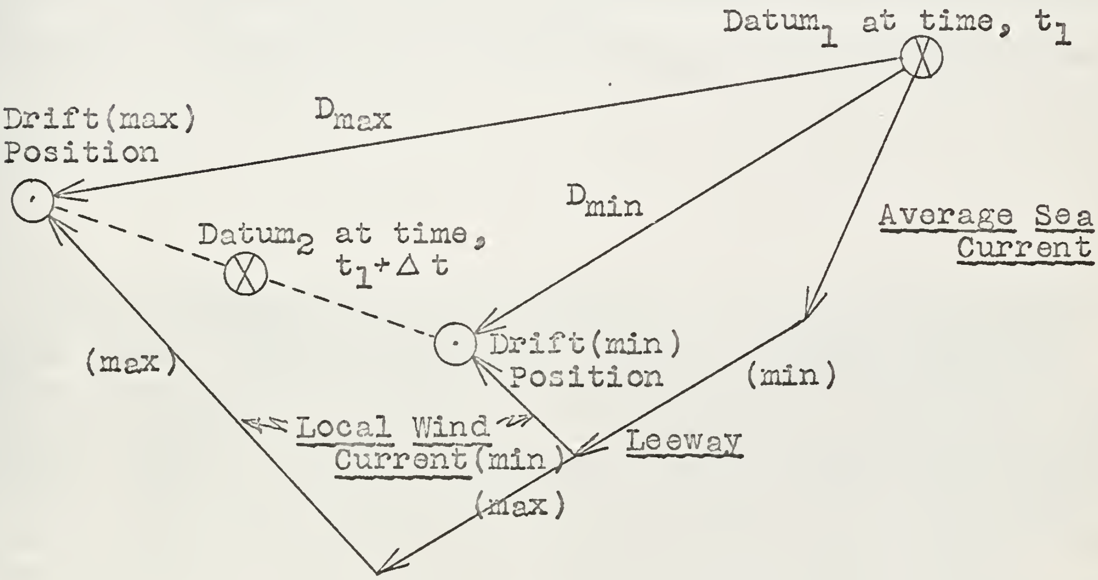

FIGURE 2

A MINIMAX PLOT OF DRIFT COMPONENTS WHEN FLUCTUATIONS ARE LARGE OR UNCERTAINTY EXISTS AS TO THE EXACT CONDITIONS AT THE SCENE

Average sea current. The average sea current is that vector described by the set and drift of the prevailing ocean currents for the area of the distress at the time of the incident. It is determined by extracting the applicable values from the appropriate charts in the Atlas of Surface Currents[4] for the area to be searched. The average sea current vector is only considered if the Atlas of Surface Currents indicates that the reported current has a steadiness equal to or greater than 35% of the time.

Local wind current. The direction and magnitude of the average sea current may be altered by the presence of local surface winds. The magnitude of the current generated by the local surface winds is a function of the force of the winds, their steadiness both in magnitude and direction, the size of the area over which they have been blowing (fetch), the length of time that they have been blowing, and the influence of the Coriolis force.

[4] Atlas of Surface Currents (Washington: U. S. Navy Hydrographic Office, 1953). This Atlas consists of a series of different atlases for various ocean areas of the world. For any given area the charts are furnished for each month of the year. These charts are divided into grids for each degree of latitude and longitude. An arrow and numbers placed in each one-degree quadrangle shows the mean direction of force of the surface current in that quadrangle for that particular month under average normal conditions and the number of observations reported for that quadrangle. A current rose shows the frequency distribution (steadiness) and average drift rate for the eight cardinal and intercardinal points for larger quadrangles.

Leeway. In addition to generating local wind currents, the local surface winds also act directly upon that portion of the survivors or their survival craft which is above the surface. The resulting displacement is called "Leeway."

Parachute drift. If the distress incident involves an aircraft distress which has required that the survivors bail out, consideration must be given to their free fall and parachute drift. The distress incident position will be the position of the aircraft at the time of bail-out, and the initial datum will be that position where the parachute would have landed after considering the altitude at which the aircraft was flying and the prevailing winds at different altitudes from the point of bail-out to the surface.

IV. ASSUMPTIONS

In approaching the first part of the problem it has been assumed that the procedures, graphs, tables and guidelines outlined in the *National Search and Rescue Manual* are based on the best information and theories available for the practical methods presently used by the United States Coast Guard in search and rescue operations. No further efforts have been directed toward verifying or disproving the existing doctrine. Instead, efforts have been concentrated on the development of an operational computer program which will facilitate the application of the existing doctrine.

In developing the computer program it was assumed that the various position and navigational errors could be approximated by normal distribution curves. Furthermore, where a vector produced two possible positions (see Figure 2, page 11), that is a maximum and a minimum position, it was assumed that the most likely position would be at a point midway between the two positions lying on a line connecting the two points.

V. LIMITATIONS

Certain self-imposed limitations were made in considering the problem. First, the problem was limited to the type where the time that the distress occurred was known, the nature of the distress and the type of units involved were known, and an estimated distress incident position was known. Furthermore, the estimated distress incident position was placed sufficiently far offshore to eliminate the effect of tidal currents, rotary currents resulting from coastal configuration, and currents caused by rivers flowing into the sea.

Additional limitations precluded the development of the parachute drift program. Recent research into this area has resulted in the development of a computer program to handle this problem. Where an aircraft is involved as the distressed unit, the program is limited to the type of distress which involves ditching the aircraft into the ocean.

No attempt was made to develop a program involving a small craft as the distressed unit since such a craft is unlikely to venture far enough

away from the coast to fall within the parameters adopted in limiting the distress incident position.

Testing of the model was done by generation of hypothetical cases, manually computing a solution using the techniques and procedures outlined in the National Search and Rescue Manual, and then comparing these results with those produced on the computer. Historical data of actual distress cases were not available at the time that this project was completed.

The program was developed for operations in the Atlantic Ocean, north of the equator only. With minor modifications, the program can be adapted for operations south of the equator and in the Pacific Ocean, both east and west of the International Date Line.

One final limitation on the study relates to the method used in measuring distances. All distances are treated as rhumb line distances based on Mercator Sailings rather than Great Circle distances. Since the magnitude of the distances involved is small, the error resulting in using Mercator distances will be neglected.

VI. RESEARCH SIGNIFICANCE

The development of an operational computer program to assist the decision-makers responsible for coordinating and conducting search and rescue operations will constitute a major step forward in improving Coast Guard operations. By eliminating the complex and tedious manual

calculations and plotting of information, it will free the Rescue Coordination Center Controller and his team to concentrate more fully on those phases of the operation which require the all important tasks of human decision-making--the final value judgments.

The development of this program opens new horizons for the use of computers in expanding search and rescue operations by presenting a workable program which may be adapted to the existing Atlantic Automated Merchant Vessel Reporting System (AMVER) and the newly developing Pacific AMVER system.

The most important significance of such a program is that it should lead to improved effectiveness in that mission of the United States Coast Guard which is directed to the preservation and safety of the lives and property of all those who travel over and upon the seas.

CHAPTER II

REVIEW OF THE LITERATURE

Studies directed toward the problem of search and rescue have been limited primarily to those conducted by the various Armed Forces and those specific agencies of other countries that have been responsible for the execution of this type of work. The United States Coast Guard has been the leader in this field both in the United States and in international efforts to develop the best techniques possible. Accordingly, the literature dealing with this problem has been produced by the combined efforts of the various services and agencies and certain individuals directly connected with these operations.

Since the problem of search and rescue is amenable to study by the various phases involved, this review of the literature will be limited to that phase dealing with the determination of the best estimated position of the survivors at any given time having started with an initial estimated position, and then the determination of a reasonable area for searching around this estimated position. Furthermore, this review will be focused on two specific areas. The first will be devoted to the doctrine prescribed in the National Search and Rescue Manual, Chapter Six, "Determination of Search Areas." It is for a portion of this Chapter that the computer program has been developed.

The second area deals with the literature which sheds new light on certain aspects of the problem which may tend to improve the existing doctrine as currently outlined in the National Search and Rescue Manual. Therefore, all literature reviewed will be that which has been developed reflecting the latest theories and ideas since the development of the National Search and Rescue Manual in 1961.

I. DOCTRINE ON THE DETERMINATION OF THE SEARCH AREA ACCORDING TO THE NATIONAL SEARCH AND RESCUE MANUAL

Before search and rescue units are dispatched to the scene of a distress and before the type of pattern of search to be used is determined, an estimated position of the survivors must be established, and an area sufficiently large to insure inclusion of the survivors must be selected. This search area is a function of the various parameters of the incident and the associated position errors. There are two possible situations confronting the decision-maker. First, the initial distress position is known with varying degrees of accuracy; and the second, the initial position of distress is completely unknown. Only the first case will be covered in this paper.

There are many factors associated with determining the initial distress position and its related position errors. The following are some of the questions which must be answered by the search and rescue (SAR)

coordinator (RCC Controller). What type of craft is in distress? What is the nature of the distress? What type of navigational information was used to determine the initial distress position? What type of survival craft is likely to be employed by the survivors? What are the existing weather conditions at the scene of distress? What has the weather been like at the scene for the preceding twenty-four hours? How long will it be before a SAR unit can reach the scene? Where is the most likely position (datum) of the survivors when the SAR units reach the scene? What are the various drift factors which must be considered in this particular case? What is the expected time of survival for the survivors considering sea water temperature and surface weather conditions at the scene?

In approaching this problem, the National Search and Rescue Manual first divides the factors affecting the position into three broad classes. The first of these is called the "Initial Error in Position"[5] and is a function of both the type of craft involved and the method of navigation used. If the reported initial position of the distress incident is based upon an accurate navigational fix, the following position errors are assumed:[6]

---

[5] National Search and Rescue Manual, op. cit., p. 6-2.

[6] Ibid., p. 6-7.

Type of distress craft	Radius of Assumed Position Error
Ship Fix	Five nautical miles
Aircraft Fix	Ten nautical miles
Small Craft Fix	Fifteen nautical miles

If the initial position of the distress incident was determined by monitor stations on radar nets or on military or commerical radio direction-finding nets, these various nets will classify their fix. These classifications have standard specified position errors.

If a fix could not be obtained at the time of the incident, or if the reported position was not specifically reported as a fix, it is assumed that the position is based on dead reckoning (DR). In this case the following position errors are assumed:[7]

Type of distress craft	Radius of Assumed Position Error
Ship DR	Five percent of the distance traveled since the last fix, plus the error of that fix.
Aircraft DR	Ten percent of the distance traveled since the last fix, plus the error of that fix.
Small Craft DR	Fifteen percent of the distance traveled since the last fix, plus the error of that fix.

The second factor affecting the distress position is that of parachute drift where the particular distress incident involves an aircraft from which the survivors have bailed out. The position reported as the initial

---

[7] *Ibid.*

position of the distress incident will not be the same position as that of the survivors when they land in the water. A table is provided to determine how far downwind the landing will be from the initial reported position of distress or bail-out point. The entering arguments for this table are altitude of parachute opening and the wind velocity in knots which represents the average wind between the winds at the altitude at which the parachute opens and the surface.[8]

The third factor, and the one most subject to question, is that of "Survival Craft Drift."[9] Once the survivors are adrift, they are subjected to the various elements of Nature. In the open sea the simplifying assumption has been made that the resultant movement of the survivors is the consequence of three forces acting upon them. These three forces influence the survivors motion or travel independently. They are (1) the force due to the average sea current which is a function of the major ocean current circulation pattern; (2) the force due to local wind currents which have been generated by the local winds in the area for the twenty-four hours preceding the distress incident; and (3) the leeway of the survival craft as it responds to the local winds at and following the time of the incident.

[8] Ibid., p. 6-3.

[9] Ibid.

The average sea current is determined by consulting the appropriate Atlas of Surface Currents for the area and month involved. If the average sea current is indicated as having a steadiness (frequency of reports) of 35% or greater, it is considered as a relevant force. Otherwise, it is disregarded.

The local wind current is treated as follows:

a. Obtain an estimate of the local wind vector for the preceding twenty-four hour period. If the vector has not varied, assume that the local wind current has diverged from the wind vector by thirty degrees to the right for latitudes north of 10°N, thirty degrees to the left for latitudes south of 10°S, or is directly downwind for latitudes 10°N to 10°S. This divergence reflects the effect of the Coriolis force.

b. If the wind vector has varied during the twenty-four hour period, determine the mean wind for four hour periods during the twenty-four hours. Then use the mean wind to determine the direction of the local wind current. If variations have been more than 45° or ten knots, intervals smaller than four hours should be used, with the final local wind current direction becoming the sum of the vectors for all the time intervals.

c. The magnitude of the local wind current is taken from a table with an entering argument of the local wind speed in knots.

d. The assumption is made that for the first six to twelve hours that a wind is blowing, the local wind current generated will be downwind. The

divergence indicated in a. above applies only after the wind has been blowing for more than twelve hours.

The component of leeway is equally complex. For survivors supported by life jackets or floating free on the surface, the sail area exposed to the winds is considered to be negligible as compared to the submerged surface area which will be subjected to the surface currents. For those survivors supported by life rafts, the leeway will be directly downwind. The magnitude of this leeway will be dependent upon whether or not the survivors have streamed a drogue. If the survivors are in a life boat, the magnitude will also be dependent upon the absence or presence of a drogue. In addition, the drift of a life boat may vary as much as forty degrees on either side of a downwind direction depending upon the configuration and loading of the life boat.

If the winds have been fluctuating, the leeway is determined for four-hour periods and then added vectorially to determine the final component. The National Search and Rescue Manual provides a graph for determining the magnitude of a typical life raft leeway (the type is not indicated) for conditions with and without a drogue.[10]

Whenever uncertainty exists as to the length of time adrift, the magnitude of the leeway, or the accuracy of the reported conditions of wind and current, leeway is approached using minimax plotting techniques.[11]

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[10] Ibid., p. 6-4.

[11] Ibid., p. 6-5.

Under these conditions the RCC Controller must determine the minimum and the maximum probable values of wind and current. From this information a plot is constructed to reflect the total minimum possible drift and the total maximum possible drift. The "most probable location of the target is the position midway between the minimum and maximum drift positions."[12]

If, however, the wind conditions have been fairly steady, an average value may be used. This will lead to a final value of the drift vector which is then considered to be an average drift vector. Both of these concepts were illustrated in Figures 1 and 2, Chapter I, page 11.

The status of the problem at this point finds the RCC Controller with an estimated position of the incident based on information received in the "Alert" phase. He also can determine the most probable location of the survivors after applying the drift factors. The next step is to evaluate the total probable error associated with the latter position.

The total probable error of position is obtained by considering the initial position error, the navigational error of the search unit(s), and the drift error associated with the determination of the drift of the survivors. The first of these, initial position error, is determined in the manner described earlier in this Chapter. The navigational error of the search unit(s) is handled in a similar manner using an identical table for determining the value of the error. The values for these two errors are

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[12] Ibid.

represented by "X" and "Y" respectively.

The drift error, d_e, can be determined one of three ways. If the total drift was determined as an average drift, the drift error is estimated to be equal to the total drift divided by eight.[13] If minimum and maximum drifts have been computed, a table is provided for determining the drift error using the minimum and maximum drift values as entering arguments.

The third method of determining drift error is used when the maximum and minimum drifts have been plotted. Using the values for the maximum and minimum drift, the respective drift errors are determined by dividing each value by eight. These values for d_e are then plotted as the radii of circles centered on their respective drift positions. The final drift error, referred to as the minimax drift error, is found graphically to be the radius of a circle centered on the line connecting the maximum and minimum drift positions and which is tangent to the outer limits of the two circles generated by the maximum and minimum drift errors. See Figure 3.

The total probable error of position can now be determined. This error, c, is determined by the equation:

$$c = \sqrt{d_e^2 + X^2 + Y^2}$$

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[13] Ibid., p. 6-7.

Although the National Search and Rescue Manual does not present the development of this equation from the theoretical background, a separate study[14] conducted in 1964 derived it mathematically. The equation was derived using the Law of Cosines and the root-mean-square of maxima and minima treating the three error vectors, two at a time.

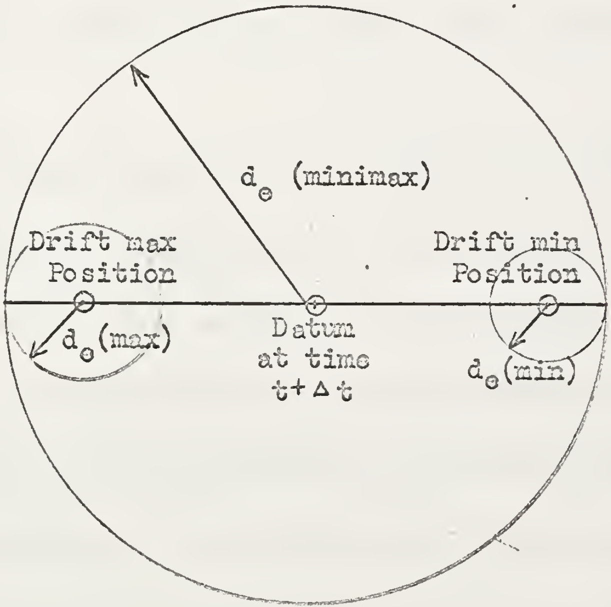

FIGURE 3

GRAPHICAL SOLUTION OF DRIFT ERROR (MINIMAX)

Furthermore, if the values for X, Y and d_e are considered to represent the standard deviation for a normal distribution associated with each of these errors, the variance would be X^2, Y^2 and d_e^2 respectively. Then c

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[14] Robert L. Armacost and Norman T. Saunders, "Computer Program of USCG Search and Rescue Procedures" (unpublished Bachelor's research paper, The United States Coast Guard Academy, New London, 1964). unnumbered.

would represent the standard deviation of a normal distribution representing the sum of these errors. The 1964 study of Armacost and Saunders also reached this conclusion.[15]

The American Practical Navigator[16] devotes a chapter to the consideration and study of navigational errors. Among the errors included in this discussion are constant errors, random errors, periodic errors, and systematic errors.

Then attention is directed to the combination of these errors in any given line of position or navigational fix. The distribution of these various errors and the application of probability of error is applied. The resulting conclusion is, "If a number of random errors are combined, the result tends to follow a normal curve regardless of the shape of the individual errors....."[17] Furthermore, applying statistical theory the authors state, "...the standard deviation of all the errors is found by squaring each individual error, adding the results, and taking the square root of the sum."[18] They further point out that a given line of position, as finally determined and plotted, "...may include 30 errors or more."[19]

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[15] Ibid.

[16] Nathaniel Bowditch and others, American Practical Navigator, H.O. Pub. No. 9, (1958 edition, Washington: U.S. Navy Hydrographic Office, 1958), pp. 678-688.

[17] Ibid., p. 683.

[18] Ibid.

[19] Ibid., p. 684.

Although Dutton, in his book, Navigation and Nautical Astronomy, does not comment directly upon the distribution of navigational errors, he does discuss celestial fixes for surface craft and the magnitude of the errors encountered. He states that, "...under average conditions an experienced navigator can obtain a fix that is seldom in error by more than a mile."[20] For celestial navigation in aircraft, "Under good conditions...a fix accurate to 5 to 10 miles is considered good..." but "...individual sights taken by experienced navigators may be more than 100 miles in error in extreme cases."[21]

In considering loran fixes he states:

> "In general, ground waves produce a line of position accurate to 1.5 miles or better over 80% of the area covered by this stations. Sky waves produce a maximum error of 5 to 7 miles for 80% of the coverage area. The accuracy of a position is increased, of course, if three or more lines of position are used and the various lines weighted by their position relative to the stations, type of wave, angle of cutting other lines, etc."[22]

Having determined the total probable error of position, the next step is to use this information in determining the limits of the area to be searched. Initially, the search area must be sufficiently large to insure that the total probable error of position is included. The theoretically ideal search area would be a circle centered at datum and with a search

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[20] Benjamin Dutton, Navigation and Nautical Astronomy (tenth edition, Annapolis: United States Naval Institute, 1951), p. 332.

[21] Ibid., p. 537.

[22] Ibid., p. 228.

radius equal to or greater than the total probable error of position, c.

The search area is expanded for each subsequent search following an unsuccessful search by increasing the search radius, R. The number of searches conducted is not limited to a specific number since adverse weather conditions at the scene may reduce the effectiveness of each sweep. Such conditions would, therefore, necessitate additional searches over and above the number used under good search conditions.

Each succeeding search will be centered on the datum point at the time the particular search is to be started. This means that the area where the survivors are most probably located, namely datum, will be searched more frequently than the outer limits of the search area. The outer limits are extended for each succeeding search. The search radius, which determines the outer limits, is found by multiplying the total probable error of position, c, by a safety factor. The safety factor is increased for each search to reflect the increased total probable error of position which has resulted from increased drift and the associated increased drift error. The values used in determining the search radius are as follows:[23]

Search	Safety Factor	Search Radius
1	1.1	1.1 x c
2	1.6	1.6 x c
3	2.0	2.0 x c
4	2.3	2.3 x c
5	2.5	2.5 x c

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[23] National Search and Rescue Manual, op. cit., p. 6-10.

The time required to complete a search will be a function of many things, such as the number of search units participating, the speeds used by the search units, the type of pattern used in the search, and the size of the area to be searched. If several hours elapse in conducting a search, it may be necessary to completely recompute the total probable error of position, ç, ,to reflect the increased drift error.

As indicated earlier, the theoretical search area would be a circle. However, to attempt to search while navigating within the limits of a circle is not particularly suitable for many of the different types of search patterns commonly used. Therefore, the search area is usually squared off to provide a rectrangular search area with a side of length 2R and a total area equal to $4R^2$. This search area provides a more suitably defined area for navigational purposes.

Figures 4 and 5 show the concept of the "repeated expansion" search concept for a stationary datum and a moving datum. This concept calls for five searches following consecutively using the search radii indicated previously. This provides for the greatest concentration of search efforts in the area where the survivors are most probably located and minimum efforts in the areas of least probable location.[24]

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[24] Ibid., p. 6-12

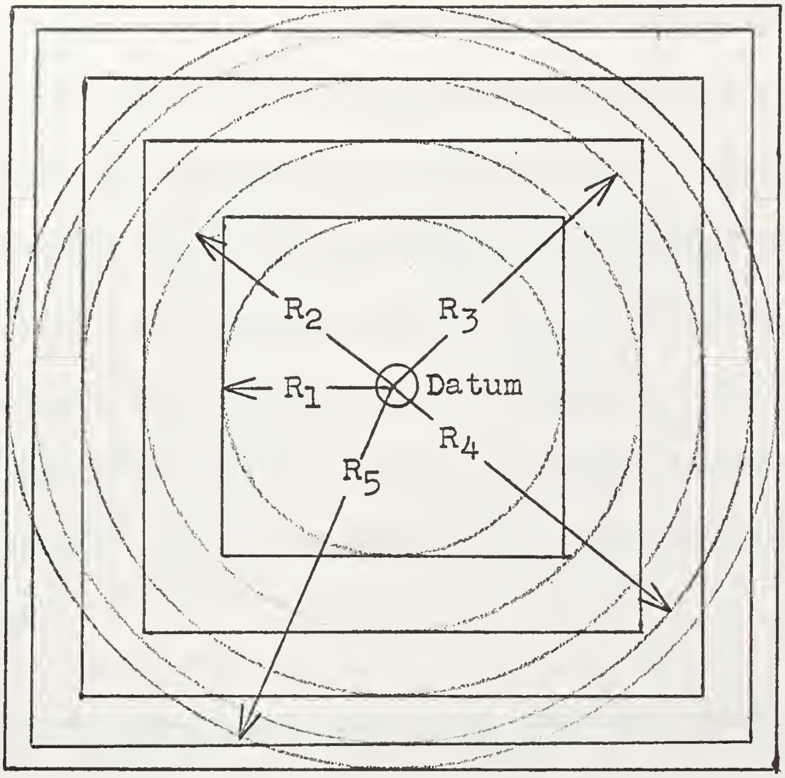

FIGURE 4

REPEATED EXPANSION SEARCH AREAS FOR STATIONARY DATUM POINT

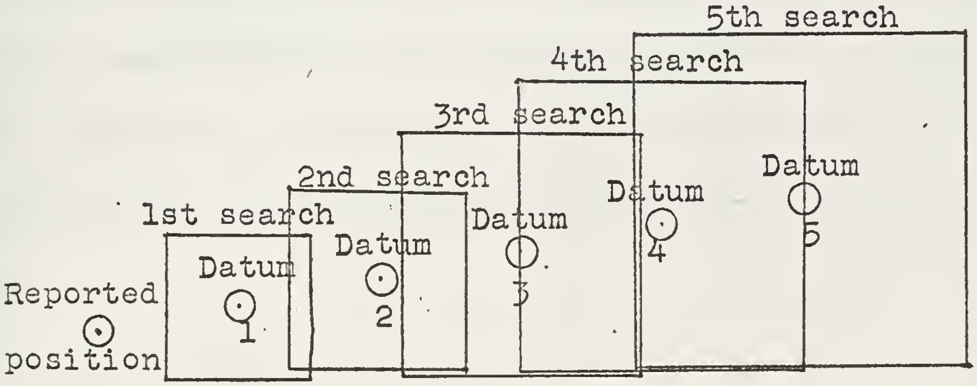

FIGURE 5

REPEATED EXPANSION SEARCH AREAS FOR MOVING DATUM POINT

Having determined the datum point and search area, the RCC Controller must then determine what search units are available, how long it will take them to reach the scene, what type of search pattern is most appropriate, and how much time is available for searching (limiting factors include aircraft fuel and hours of daylight remaining before dark). Considering these factors, the RCC Controller must make a value judgment of the search area calculations and perhaps modify the area by altering the size of the search radius or the track spacing of the search units or both. This is known as a "feasibility check."[25] This is a decision which must be made on the basis of the specific situation which exists for each individual distress incident.

II. STUDIES DEALING WITH PARACHUTE DRIFT AND OCEAN CURRENT DRIFT

Parachute drift.

In 1964, while at the United States Coast Guard Academy, Cadets, First Class, Armacost and Saunders, conducted a study[26] of the general problems associated with search and rescue operations. A major portion of their efforts was directed in examining the problem of free-fall and parachute drift of survivors who were required to bail out of a distressed aircraft.

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[25] Ibid., p. 7-11.

[26] Armacost and Saunders, op. cit.

Their examination of the table provided in the National Search and Rescue Manual lead them to believe that the values contained therein were related linearly. They also concluded that the table was based on a model where the survivor's initial velocity at time of bail-out was zero in both the horizontal and vertical planes. Also, the table utilizes an average wind between bail-out altitude and the surface. It makes no provision for the wide variance in both wind velocity and direction which may be encountered at different altitudes.

Accordingly they set out to derive equations which would relate the force of gravity, effect of winds in a horizontal direction, motion due to the velocity of the aircraft, and air resistance. They did this by developing equations for the vertical component of free fall, the horizontal component of motion due to wind, the horizontal component of motion due to an initial velocity equal to that of the speed of the aircraft, the effect of air resistance or drag as a function of air density which in turn is a function of barometric pressure and temperature, the relationship of kinematic viscosity of air, air density and altitude, and finally, the evaluation of the various constants appearing in the various equations. Having completed this extensive development, they then wrote a basic flow diagram for their program. That portion of their work dealing with the parachute drift problem has been reproduced in its entirety in Appendix C.

In 1965, Cadet, First Class, Darvy M. Cohan, also of the United States Coast Guard Academy, continued the work started by Armacost and Saunders. Cohan refined and developed a computer program[27] incorporating the results of Armacost and Saunders; but, in addition, he investigated the effects of changing wind direction and velocity using three different altitudes: (1) surface winds, (2) medium altitude winds, and (3) high altitude winds. These winds were selected since information on their magnitudes is usually available from various agencies providing meteorological data.

In addition, he considered the effects of three possible parachute opening conditions which included the two possible extremes, namely (1) that the parachute opened immediately upon leaving the aircraft, or (2) the parachute did not open at all, and the possibility of opening automatically at 14,000 feet. This latter altitude is the one at which most military parachutes are designed to open using a barometric automatic release mechanism.

Cohan employed the Euler method of integration in his program. He tested his program on an IBM 1620 computer and found that the running time was slightly less than ten minutes. Accordingly, he recommended

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[27] Darvy M. Cohan, "Free Fall and Parachute Drift" (unpublished Bachelor's research paper, The United States Coast Guard Academy, New London, 1965).

that future work in this area should include consideration of utilizing more sophisticated techniques such as the Runge-Kutta method. Furthermore, he pointed up the weakness that exists in that no consideration has been given to the effect of turbulent weather conditions with the associated vertical shear, updrafts, and downdrafts which may have contributed to precipitation of the distress itself.

Appendix D contains the basic equations, flow diagrams, and computer program for the IBM 1620 which Cohan developed.

Ocean current drift.

As military and commercial maritime operations continue to grow, the need for more and more accurate information dealing with surface (and sub-surface) currents--their prediction and behavior--increases in importance. Oceanographers and meteorologists have long been studying this problem. Many theories have been advanced; however, obtaining sufficient experimental data to test these theories has proved to be a major obstacle.

The Fleet Numerical Weather Facility (FNWF) at Monterey, California, has recently developed a computerized system for producing synoptic analyses of surface currents based on the distribution of sea surface temperatures and the climatological temperature field at a depth

of 200 meters. Commander W. E. Hubert, USN, presented a paper[28] at the Institute of Navigation in San Francisco in December 1964 is which he discussed the general method used in the Fleet Numerical Weather Facility's program. This program is designed to evaluate the transport due to the permanent flow component and the component due to wind and waves thus producing the overall pattern of surface currents. Commander Hubert's paper appears in Appendix E.

Taivo Laevastu has conducted an extensive review of the materials dealing with surface currents in connection with his work at the Fleet Numerical Weather Facility and his preparation of the book Oceanographic Forecasting for the Navy Oceanographic Office. In Chapter Ten, Doctor Laevastu examines in detail the various aspects of "Prediction of Surface Currents."[29] Among the factors investigated, he discusses the evaluation of permanent flow, wind currents, mass transport by waves, inertia currents, tidal and "hydraulic currents," currents caused by the change in atmospheric pressure, and other current components.[30] He further discusses the

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[28] W. E. Hubert, "Computer Produced Synoptic Analyses of Surface Currents and Their Application for Navigation" (paper read at the 1964 National Marine Navigation Meeting, Institute of Navigation, San Francisco, December 7-8, 1964).

[29] Taivo Laevastu, "Prediction of Surface Currents," Oceanographic Forecasting (a book presently under preparation for U.S. Naval Oceanographic Office under Contract Number N62306-1129).

[30] Ibid., pp. 10-1 - 10-26.

evaluation of change of current speed and direction with depth, the influence of water depth, configuration of coast and islands, nearshore circulation, current boundaries and eddies, and deep currents.[31]

Further studies relating the work of the Fleet Numerical Weather Facility and the problems associated with surface weather phenomena are found in their Technical Notes Numbers Five[32] and Eight[33] published in February 1965. These Technical Notes discuss the sea-air interactions on a synoptic scale and the analyses and forecasting of sea surface temperatures, both of which are directly related to the paper presented by Commander Hubert in December 1964 and referred to earlier.

The U. S. Naval Oceanographic Office has been vitally interested in the problems associated with ocean current prediction. Although military operations involving anti-submarine warfare have given impetus to studies in this area, the problems associated with prediction of the location of freely drifting mines and rafts and the associated areas for searching for these objects have also been under investigation.

Donald A. Burns of the U. S. Naval Oceanographic Office has

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[31] Ibid., pp. 10-23 - 10-32.

[32] W. E. Hubert, "U. S. Fleet Numerical Weather Facility Activities Relating to Sea-Air Interactions on a Synoptic Scale" (Technical Note Number Five. Monterey: Fleet Numerical Weather Facility, 1965).

[33] P. M. Wolff, L. P. Carstensen and T. Laevastu, "Analyses and Forecasting of Sea Surface Temperature (SST)" (Technical Note Number Eight. Monterey: Fleet Numerical Weather Facility, 1965).

developed a Fortran Computer Program which defines a drift ellipse pattern for the free-floating object.[34] The essentials of this drift ellipse program are described in A Statistical Rose Program developed by Walter E. Yergen and published by the Oceanographic Office.[35]

Basically, Burns' program analyzes input data consisting of "grouped frequency current observations."[36] This analysis produces various parameters which are then plotted to outline that area in which recovery is most probable. This is accomplished by determining vector means, vector variances and covariances, determining the inclination of the principle axis of the distribution, and the standard deviations along these principle axis. Next, within specified limits for speed and direction classes, the frequencies for the normal surface are integrated.[37] This Drift Ellipse Program is found in Appendix F.

III. NOTE ON ADDITIONAL LITERATURE RELATING TO THE OVERALL SEARCH AND RESCUE PROBLEM

In undertaking this project it was necessary that a thorough general

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[34] Donald A. Burns, "Instructions for Surface Drift Ellipse Program" (Washington: U. S. Naval Oceanographic Office, June 1962).

[35] Walter E. Yergen, A Statistical Rose Program, SP-64 (Washington: Evaluation Branch, Oceanographic Analysis Division, Marine Sciences Department, U. S. Naval Oceanographic Office, October 1962).

[36] Burns, op. cit., passim.

[37] Yergen, op. cit., passim.

understanding of all aspects of the search and rescue problem be acquired before an attempt was made to sub-optimize that portion which was selected. Accordingly, the Bibliography at the end of this paper is annotated to reflect all the pertinent literature which was reviewed in the process of this study.

CHAPTER III

THE STUDY

I. METHOD

The method of research employed in this study was basically that of the development of a conceptual model designed for a computer solution expressing the doctrine outlined in the National Search and Rescue Manual for the determination of a search area. Through the application of mathematical techniques relationships of the numerous variables were developed. These relationships were then outlined in a series of computer flow diagrams, for various subroutines, and the computer programs were written in Fortran 60 computer language. After each subroutine was thoroughly checked and tested, the final program was assembled, tested and evaluated using hypothetical distress cases.

II. PROCEDURE

The problem of determining a search area for any given distress incident involves three basic steps:

1. Determine the datum point at any specified time.
2. Determine the probable position errors associated with the datum point.
3. Determine the limits of the area which will be included in the search.

Each of these steps was examined individually and in detail. The examinations were accomplished incrementally by determining what output was required, what were the inputs available or necessary to develop the desired output, and how were the inputs and output related. The limitations outlined in Chapter I were carefully observed.

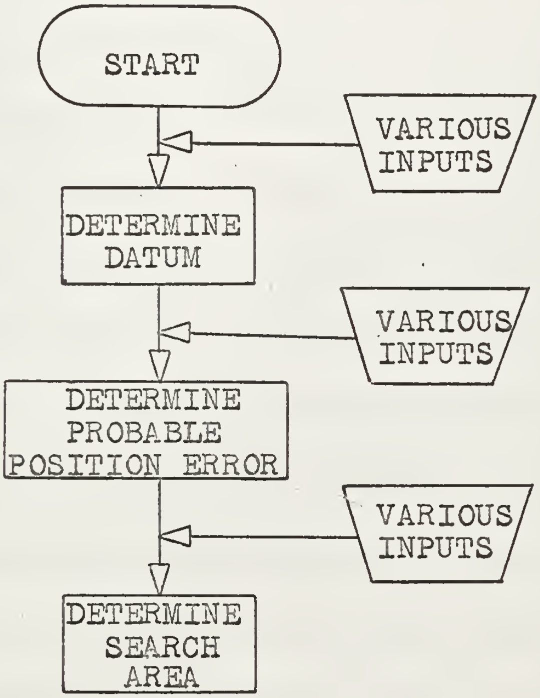

FIGURE 6

THE BASIC PROCESS OF DETERMINING THE SEARCH AREA

The following sections of this chapter will treat each of the above areas in order. Program flow diagrams will reflect the general logical sequence which was employed although the terminology used will be broad enough

to permit the development of similar programs using computer languages other than Fortran 60. Standard symbols will be used throughout the diagrams. An index to these symbols will be found in Appendix A. The detailed computer program in Fortran 60, complete with definitions of the applicable variable names used, will be found in Appendix B.

Determination of datum at any specified time, t_i.

When a distress case has entered into the "Distress" phase, the RCC Controller's first task is to determine the datum point. Since this datum point will be continuously moving as time passes, he must select the specified time, t_i, for which datum is to be determined. The initial reported position of the distress incident will be datum t_o where t_o is the time at which the distress incident occurred. The time selected, t_i, may be the estimated time of arrival of search units at the scene, or it may be the predicted position at any other time during the period of the case duration. It will be redetermined during each search and used as the center of subsequent searches. What then is the information needed by the RCC Controller to determine datum t_i?

The basic information needed will be the initial distress incident position, datum t_o, or the previous datum if this is a redetermination of datum, the time of the previous datum, the time for which the new datum is being determined, and the drift vectors which have been acting

upon the previous datum during the time interval which will have elapsed. See Figure 7-A.

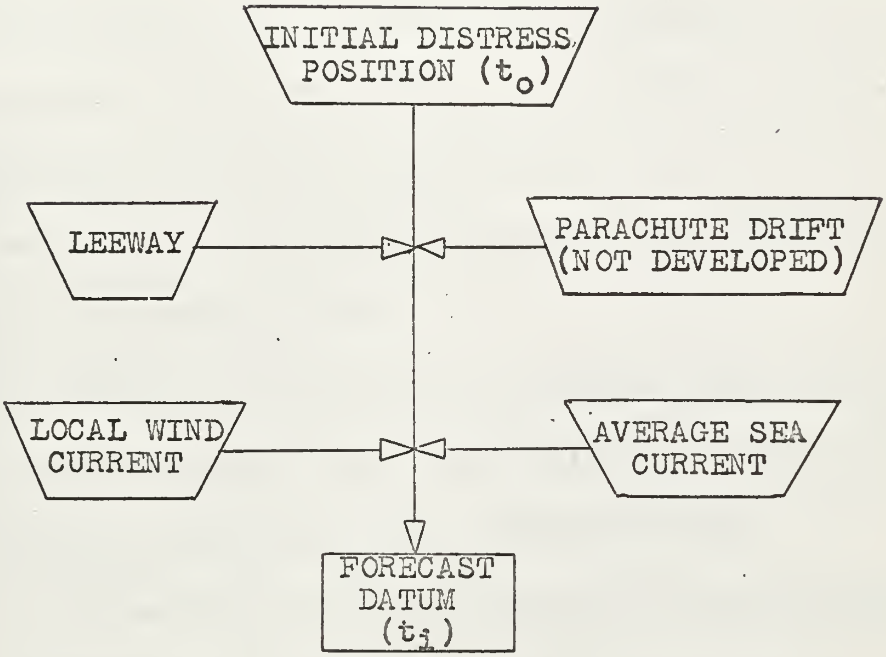

FIGURE 7-A

THE FACTORS ASSOCIATED WITH THE FORECASTED DATUM

The following specific information is necessary:

1. The type of unit in distress, i.e., an aircraft, a ship, or a small craft (this latter portion was not developed in this study).

2. The initial distress incident position. This position will be expressed in terms of latitude and longitude.

3. The time associated with the initial distress incident position in terms of the date, hour and minute expressed in Greenwich Mean Time (GMT).

4. Based on the type of unit in distress and a knowledge of the type of survival equipment carried on that type of distressed unit, the RCC Controller must specify what type of survival craft is believed to be the object of the search. This information may have been furnished in the message reporting the distress incident.

5. Weather information at the scene of the distress incident including:

a. The present surface wind velocity expressed in knots and the direction from which it is blowing in degrees from true North.

b. The surface winds for the twenty-four hour period preceding the time for which the datum is being determined. The velocity and directions are needed and must be expressed in knots and degrees from true North.

6. The average sea current set and drift expressed in knots and degrees from true North. This information is extracted from the Atlas of Surface Currents for the appropriate area and month. At the same time the steadiness of this current is also determined and noted.

7. The specific time, t_i, for which datum is to be determined. This will be expressed in terms of date, hour, and minute using GMT.

Using these specific inputs, the drift components of leeway, local wind current, and average sea current are determined as follows:

Leeway. Since leeway is the motion of the survival craft resulting from the action of the surface wind upon the craft, the first factor to be considered is the type of survival craft believed to be employed. If the survivors are believed to be floating in the water, either unaided or with life jackets, the effect of the local surface winds is assumed negligible. In this case the leeway component becomes zero and the computations continue to the next part of the program.

If, however, the survival craft is believed to be either a raft or a boat, a leeway component will exist and must be determined. Considering the case of a raft first, its motion will be directly downwind. Therefore, the input of the local surface wind direction plus 180 degrees will yield the direction of the leeway component. The rate at which the raft will drift is a function of the local surface wind velocity and also depends upon whether or not the survivors in the raft stream a drogue to retard their motion in leaving the site of the distress incident. Therefore, two possible drift rates must be considered; (1) the rate of drift with a drogue, and (2) the rate of drift without a drogue. This results in the determination of a maximum value and a minimum value of the leeway component. When the leeway components (in knots) are multiplied by the elapsed time, Δt, the total maximum and minimum leeway components are determined.

The treatment in the case of a boat is similar to that of a raft. However, the direction of drift of a boat has been found to vary as much

as 40° on either side of the downwind direction. Therefore, the maximum and minimum leeway vectors must also include maximum and minimum vectors 40° on either side of the downwind direction to reflect this divergence. This provides a total of six leeway vectors of which the two downwind vectors are used in computing datum while all six vectors are considered in the determination of the drift error.

In this specific study, the magnitude of the minimum leeway component was determined by one of two equations based on leeway curves given in the National Search and Rescue Manual.[38] Analysis of the curves showed that leeway for a raft with a drogue could be closely approximated by two straight lines. The first line approximated leeway for wind velocities equal to or less than five knots:

$$\text{Leeway in } \frac{\text{n. miles}}{\text{hr.}} = \frac{(\text{wind velocity in knots} \times 0.8)}{24}$$

The second line approximated leeway for surface wind velocities greater than five knots:

$$\text{Leeway in } \frac{\text{n. miles}}{\text{hr.}} = \frac{(\text{wind velocity in knots} + 2.5)}{1.87 \times 24}$$

The magnitude of the maximum leeway component (no drogue streamed) was also determined from the curves. However, the leeway curve values had been stored in memory and were furnished directly as a function of the wind velocity. Figue 7-B is the flow chart for the program used in determining the leeway components.

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[38] National Search and Rescue Manual, op. cit., p. 6-4.

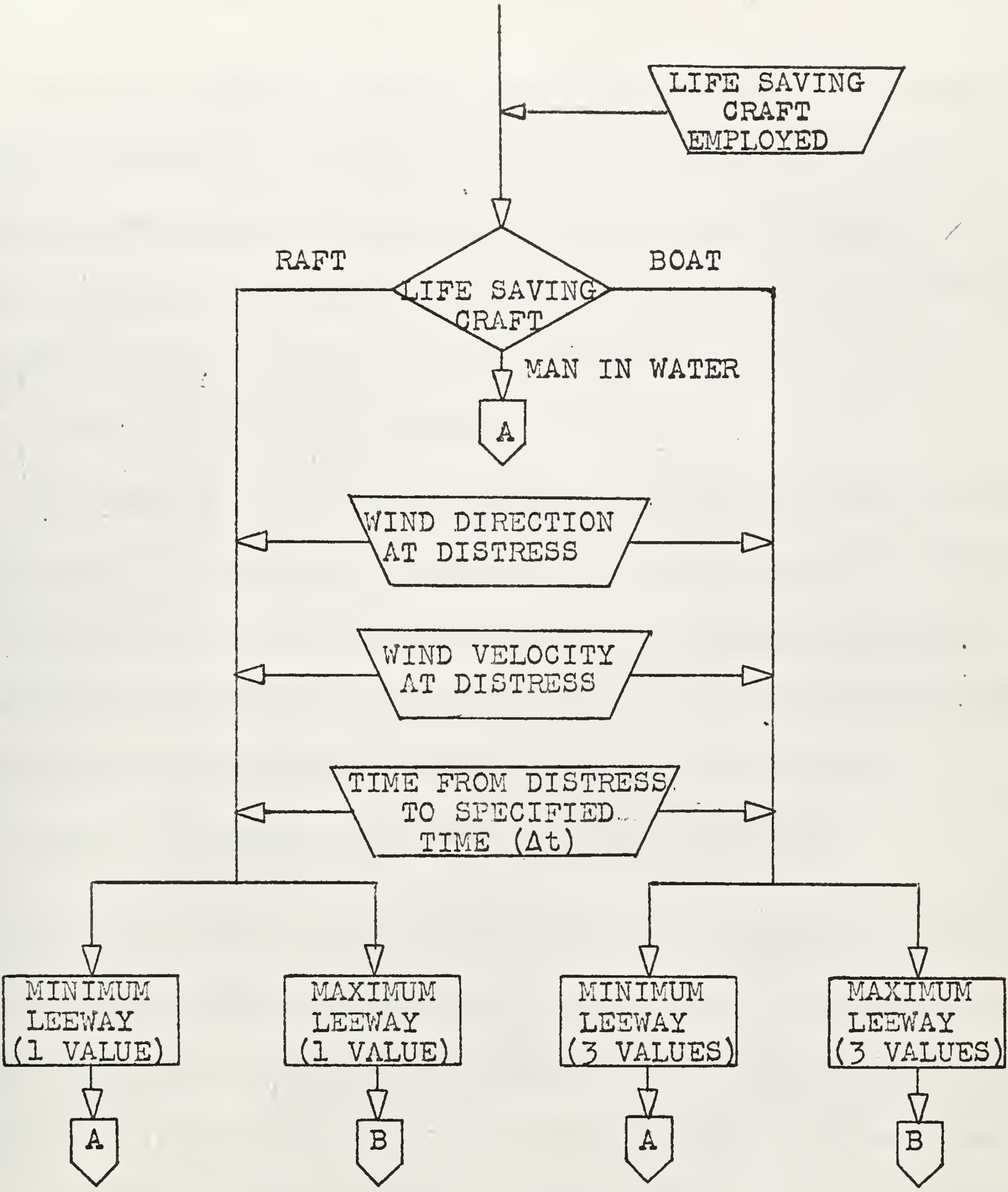
LIFE SAVING CRAFT EMPLOYED
RAFT
LIFE SAVING CRAFT
BOAT
MAN IN WATER
A
WIND DIRECTION AT DISTRESS
WIND VELOCITY AT DISTRESS
TIME FROM DISTRESS TO SPECIFIED TIME (Δt)
MINIMUM LEEWAY (1 VALUE)
MAXIMUM LEEWAY (1 VALUE)
MINIMUM LEEWAY (3 VALUES)
MAXIMUM LEEWAY (3 VALUES)
A
B
A
B

FIGURE 7-B

FLOW DIAGRAM FOR DETERMINING LEEWAY DRIFT COMPONENTS

Applying the elapsed time to the leeway magnitudes and then combining this product with leeway direction yields the leeway vectors.

Local wind current. The local wind current is treated in the manner described in Chapter II. However, the mean wind direction and velocity are determined manually with the number of calculations involved depending upon the extent of the surface wind variations during the preceding twenty-four hour period. The mean wind for the preceding twenty-four period is then used as an input for the computer.

The magnitude of the current generated by the local wind is a function of the mean wind velocity. Examination of the table relating the velocity of the wind current to the mean wind speed in the National Search and Rescue Manual suggested a linear relationship.[39] The data from the table were plotted and the following equation provided the relationship:

$$\underset{\text{(in knots)}}{\text{Velocity of the local wind current}} = \frac{(\text{mean wind}/1.18)}{24}$$

The latitude of the initial distress position (or previous datum) was compared to the 10°N latitude criterion to determine the divergence of the local wind current resulting from the Coriolis force. If the distress incident latitude was less than or equal to 10°N, the direction of the local wind current became the direction of the mean local wind + 180°. If the distress incident latitude was greater than 10°N, the direction of the local wind

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[39] Ibid.

current diverged 30° to the right of the downwind direction of the mean local wind.

By applying the elapsed time to the local wind current velocity and then combining this with the direction of the local wind current, the final local wind current drift vector was determined. See Figure 7-C.

Average sea current. This component is simply the values determined from the Atlas of Surface Currents for set and drift with the latter portion multiplied by the elapsed time. If the degree of steadiness was less than 35%, this component is assigned a zero value by the RCC Controller. See Figure 7-D.

Resultant total drift. The final resultant total drift vector for the elapsed time period is the vector sum of the leeway components, the local wind current component, and the average sea current component. Since this involves maximum and minimum components, maximum and minimum total drift vectors will be generated. In accordance with the assumptions stated in Chapter I, the new datum will be found at a point midway between the maximum drift position and the minimum drift position found by using the downwind leeway vectors. See Figure 2 in Chapter I, page 11, for the general drift picture. Figure 8 shows the drift picture for a life raft, and Figure 9 shows the drift picture for a boat with the associated divergence of the leeway vectors. In the latter case the most

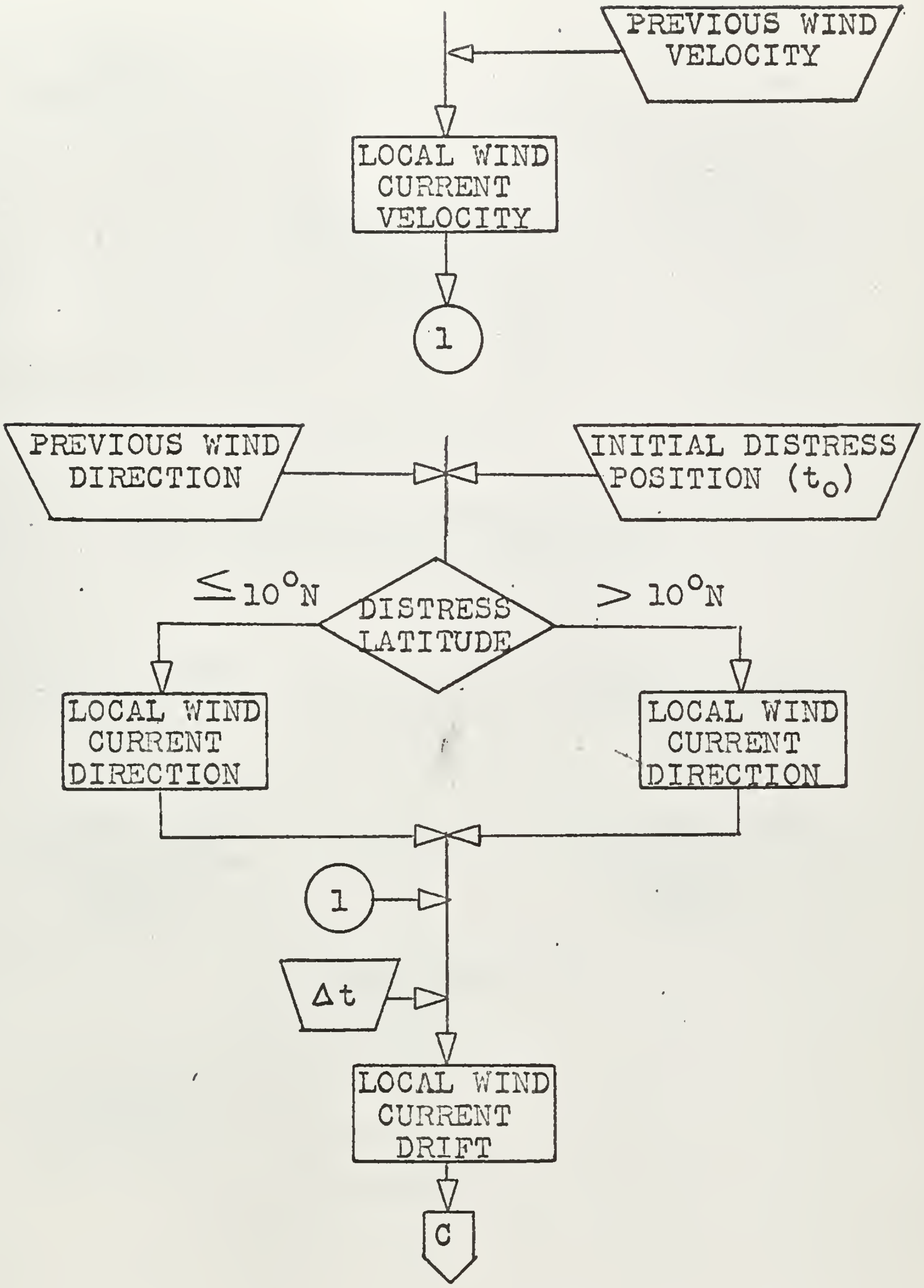
PREVIOUS WIND VELOCITY
LOCAL WIND CURRENT VELOCITY
1
PREVIOUS WIND DIRECTION
INITIAL DISTRESS POSITION (t_o)
≤ 10°N
DISTRESS LATITUDE
> 10°N
LOCAL WIND CURRENT DIRECTION
LOCAL WIND CURRENT DIRECTION
1
Δt
LOCAL WIND CURRENT DRIFT
C

FIGURE 7-C

FLOW DIAGRAM FOR DETERMINING LOCAL
WIND CURRENT DRIFT COMPONENT

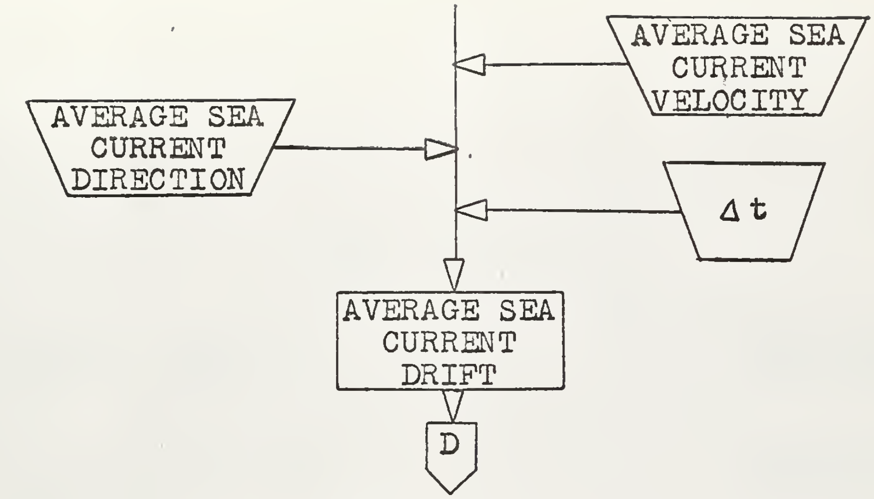
AVERAGE SEA CURRENT VELOCITY
AVERAGE SEA CURRENT DIRECTION
Δt
AVERAGE SEA CURRENT DRIFT
D

FIGURE 7-D

FLOW DIAGRAM FOR DETERMINING THE AVERAGE SEA CURRENT DRIFT COMPONENT

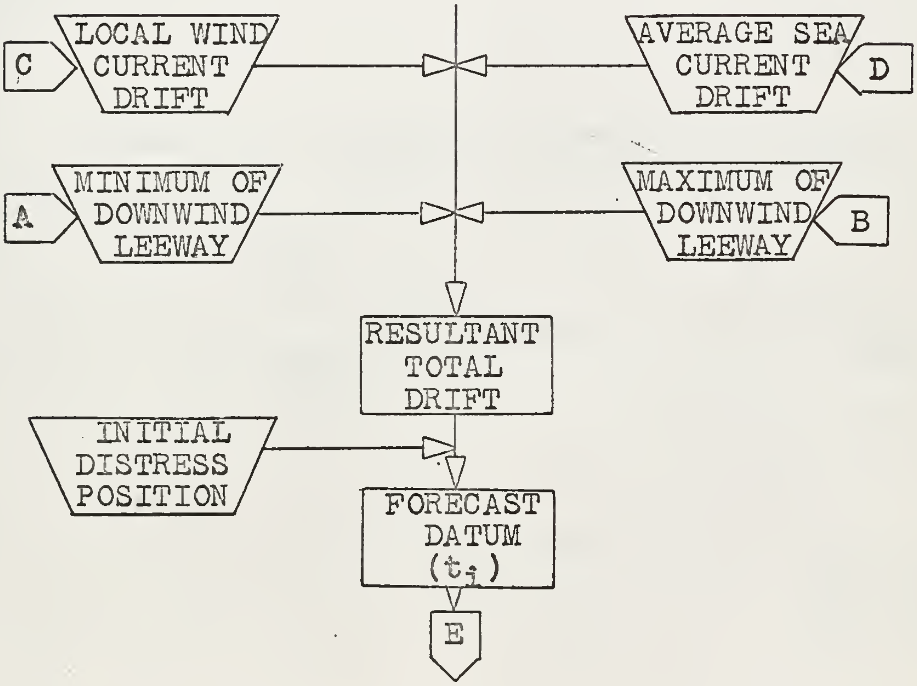
C
LOCAL WIND CURRENT DRIFT
AVERAGE SEA CURRENT DRIFT
D
A
MINIMUM OF DOWNWIND LEEWAY
MAXIMUM OF DOWNWIND LEEWAY
B
RESULTANT TOTAL DRIFT
INITIAL DISTRESS POSITION
FORECAST DATUM (t_i)
E

FIGURE 7-E

FLOW DIAGRAM COMBINING DRIFT VECTORS AND DATUM$_{t_o}$ YIELDING FORECASTED DATUM$_{t_i}$

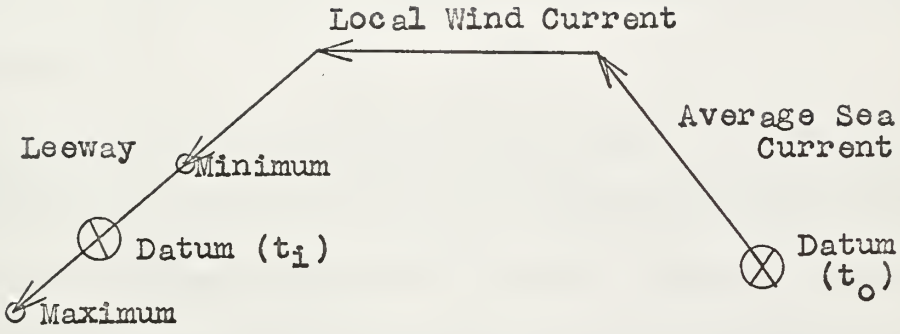

FIGURE 8

COMPLETE DRIFT PICTURE FOR LIFE RAFT

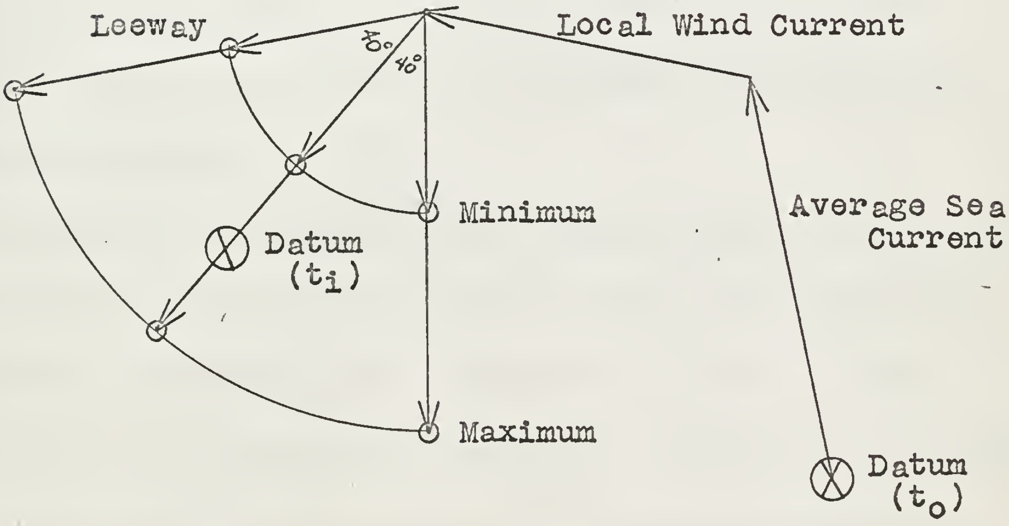

FIGURE 9

COMPLETE DRIFT PICTURE FOR LIFE BOAT

probable position of the survivors is assumed to lie midway between the maximum and minimum positions on the downwind vector. However, the extreme drift positions associated with the divergence of the leeway vectors serve as input data for a portion of the problem phase relating to position errors.

In the specific program developed by this study the problem of vector addition was treated in two steps. The first step was to convert the directions of the vectors, which were expressed in degrees measured clockwise from True North, to the standard Cartesian coordinate system used by the computer. Computer angles are measured in radians. The conversion was accomplished by the relationship:

$$\phi_R = \frac{5\pi}{2} - \theta_R$$

Where ϕ_R is the angle expressed in radians as used in the computer calculations, and θ_R is the direction of the component converted from degrees True into radians.

The second step in treating the vector addition problem was to convert the various components of leeway, local wind current, and average sea current into their respective x and y components. The final resultant vector is obtained by summing the x components, summing the y components, and then applying the Pythagorean Theorem to find the resultant vector.

Actually, the various drift vectors were broken into the x and y components and carried as subscripted variables throughout the program and applied where needed.

Determination of total probable error of position.

The total probable error of position is a function of three basic errors: (1) the initial error associated with the distress incident position, (2) the navigation error associated with the search units, and (3) the error associated with the determination of the drift components. See Figure 10-A.

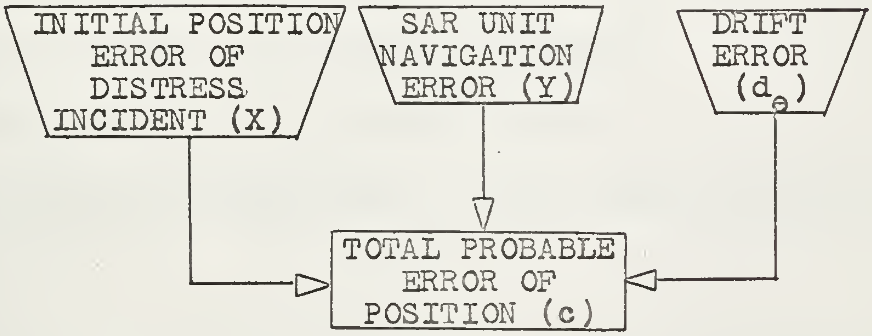
INITIAL POSITION ERROR OF DISTRESS INCIDENT (X)
SAR UNIT NAVIGATION ERROR (Y)
DRIFT ERROR (d_e)
TOTAL PROBABLE ERROR OF POSITION (c)

FIGURE 10-A

COMPONENTS OF TOTAL PROBABLE ERROR OF POSITION

The following specific information is needed to determine the values of these errors:

1. The type of unit in distress.

2. The type of search unit which will be dispatched.

3. The classification of the method of navigation employed to determine the initial distress incident position. If the method of navigation is unclassified or is classified as dead reckoning (DR), the last known fix of the distress unit must be ascertained.

4. The classification of the method of navigation which will be employed by the search unit in proceeding to the scene of the distress incident.

5. The present position of the search unit must be determined. This present position of the search unit is treated as a fix. It must be expressed in terms of latitude and longitude.

6. The magnitude of the maximum drift vector.

7. The magnitude of the minimum drift vector.

Applying these specific inputs, the three types of errors are determined as follows:

Initial position error of the distress incident. This error is strictly a function of the type of craft in distress and the method of navigation used to determine the initial position of the distress incident. In a general program the procedure is to test for the type of craft in distress which then determines which portion of the program is to be used. The next step is to determine the classification of the method used in determining the reported incident position. Using the values for initial position error cited in Chapter II for the appropriate navigational method produces the desired initial position error, X.

If the classification of the navigational method is that of a position based upon radio direction-finder bearings (DF), the type of DF system used must be further identified. The two types of DF systems commonly

used are the commercial-military DF service nets and the Federal Communications Commission (FCC) nets. Each of these nets will furnish a classification of their position fix which indicates the error associated with the position. These classifications, which are used in the program, are given below.[40]

Fix Classification	Associated Position Error As A Radius In Nautical Miles	
	DF Service Net	FCC-DF Net
Class A	Within 5	20 or less
Class B	Within 20	40 or less
Class C	Within 50	60 or less
Class D	- - - -	more than 60

Since the DF classification system is independent of the type of craft involved, one portion of the computer program handling this type of position classification serves for all other branches of the system regardless of the type of craft involved.

Originally the specific program developed by this study followed the general program shown in Figure 10-B. The various navigational classifications were assigned different code numbers or combinations of codes. These codes were then punched into the input data cards. Since

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[40] *Ibid.*, p. 5-7.

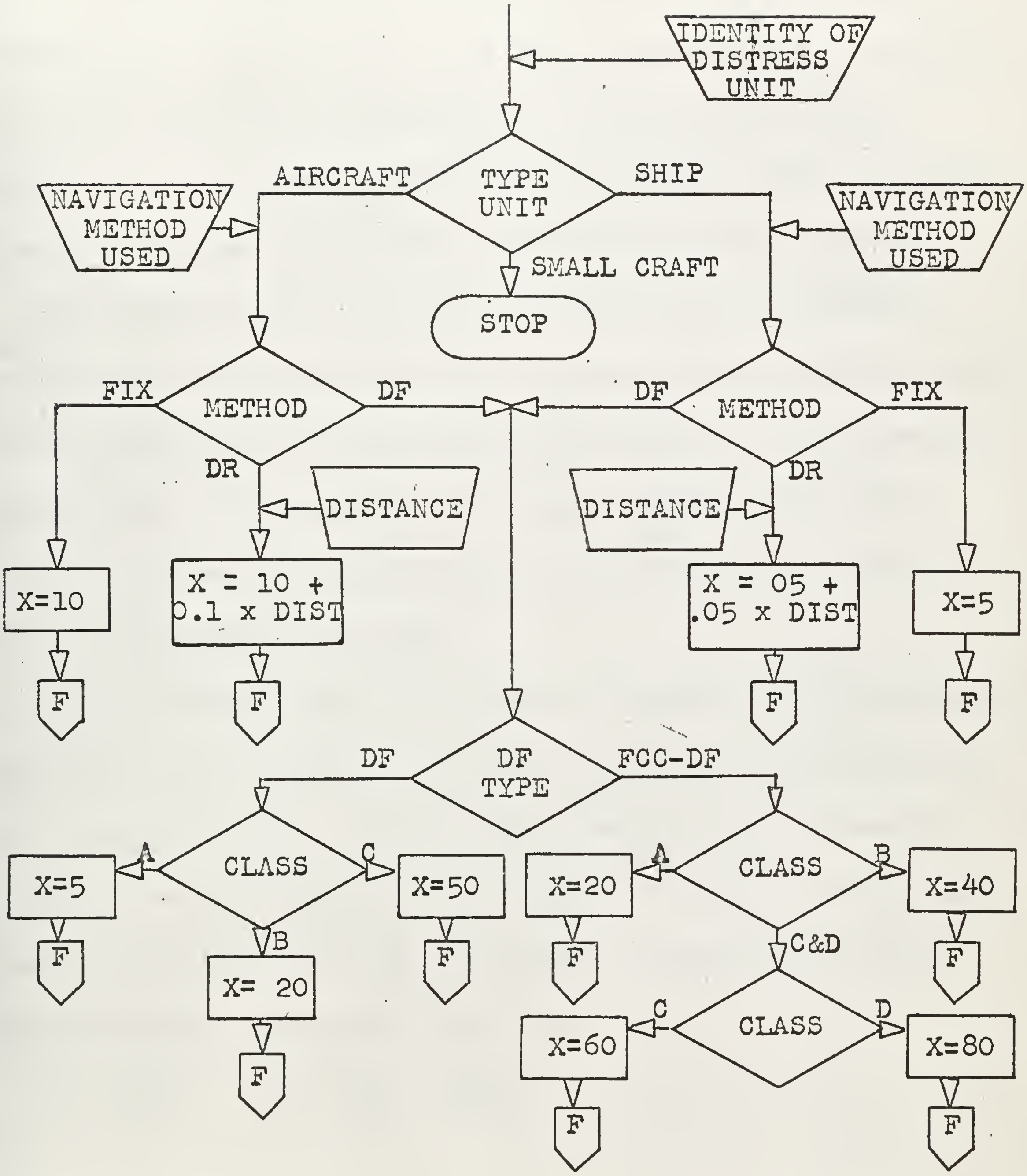

FIGURE 10-B

FLOW DIAGRAM FOR THE DETERMINATION OF THE INITIAL POSITION ERROR, X.

it was obvious that the operator in the RCC would have to put in these classification code numbers in one form or another, it was decided to change the code numbers to the actual values of the error for the methods which were classified as a Fix or DF Fix. This limited the program calculations to those involved with DR classifications. This will probably be the classification most generally encountered in actual practice.

In the case of a DR classification, the error is equal to the error associated with the last known fix plus a certain percentage of the distance traveled from that last fix to the reported DR position. The percentage of the distance used is dependent upon the type of craft involved. The problem encountered in this determination is ascertaining the distance traveled between those two points.

There are various methods available for determining distances between points on the Earth's surface. The method selected for this program was that of Mercator Sailing. The only inputs needed for the computer were the latitudes and longitudes of the two points. The basic equations used in solving this problem were those developed by Bowditch in his book, American Practical Navigator.[41] They are:

$$D = \frac{\ell}{\cos C}, \quad \text{and} \quad \tan C = \frac{DLo}{m},$$

---

[41] Bowditch, op. cit., p. 227.

where: D = the distance in nautical miles between 1 and 2.

ℓ = the difference in latitudes, L_1 and L_2, in minutes.

DLo = the difference in longitudes, λ_1 and λ_2, in minutes.

m = the difference in meridional parts, M_1 and M_2, (where meridional parts are a measure of the arc length of a meridian between a given latitude, L_i, and the equator measured on a Mercator chart, expressed in units of 1' of longitude at the equator).[42]

M_i = the number of meridional parts between the equator and latitude, L_i.

The values of M_i were obtained by using the first two terms of the equation:[43]

$$M_i = 7915.704468 \log \tan(45^\circ + L_i/2) - 23.268932 \sin L_i - 0.052500 \sin^3 L_i - 0.000213 \sin^5 L_i - \ldots$$

Navigational error of the search unit. This error follows the same identical pattern of solution as that utilized in the determination of the initial position error, X. The general flow diagram is shown in Figure 10-C. Only the position of the last known fix of the unit concerned will vary.

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[42] Ibid., p. 936.

[43] Ibid., p. 1187. "The constants used...are based upon Clarke's spheroid of 1866...the standard reference spheroid used for charting North America." In the computer program only the first six significant digits were used for each constant.

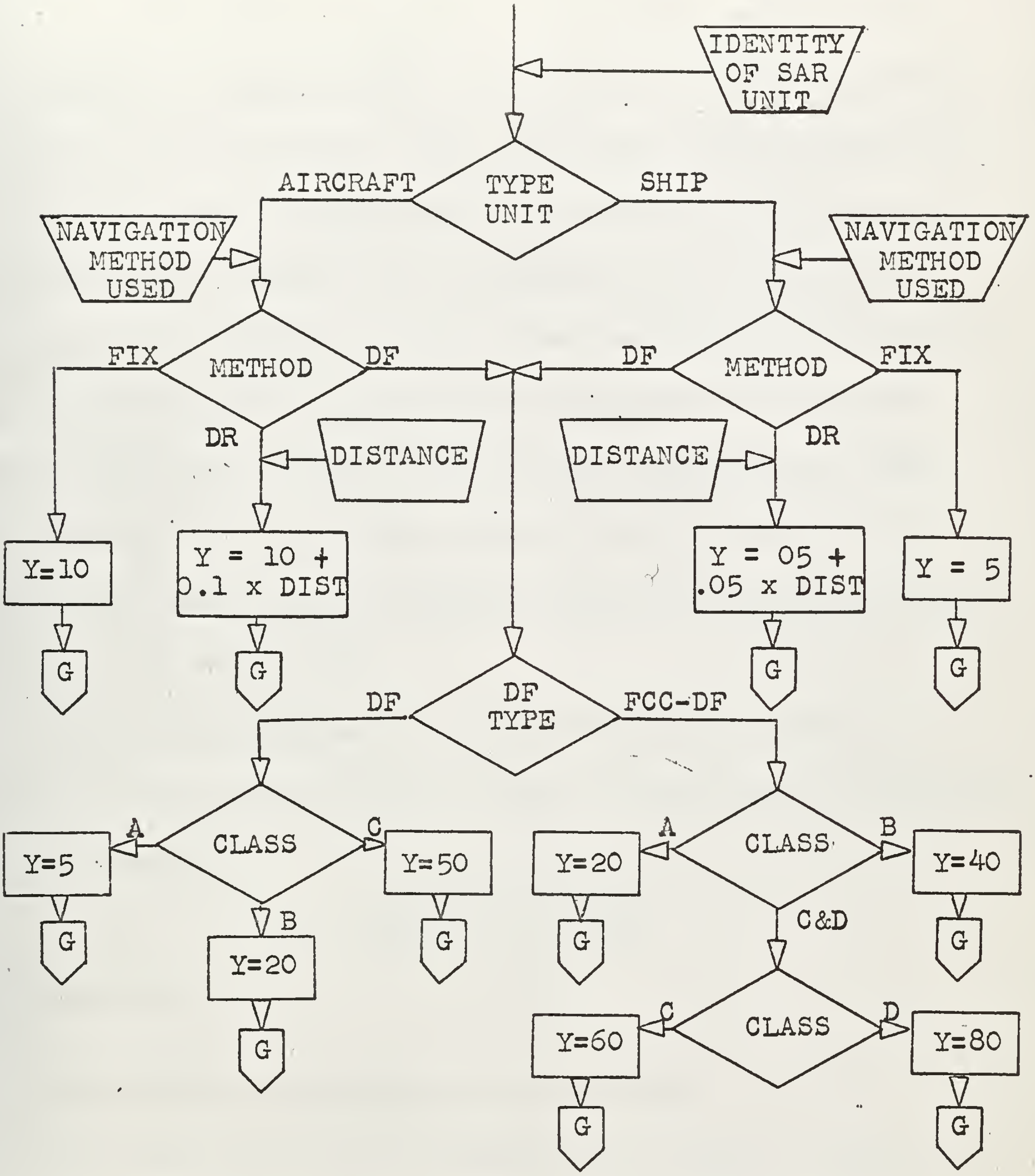

FIGURE 10-C

FLOW DIAGRAM FOR THE DETERMINATION OF THE NAVIGATIONAL ERROR OF THE SEARCH UNIT, Y.

Drift error. The methods available for the determination of drift error, d_e, were outlined in Chapter II. The computer solution for d_e was achieved by using the vector summation of the various components of drift as discussed earlier. These vector sums produced maximum and minimum drift vectors. In the case of a raft there are two vectors, one maximum and one minimum. For a boat there are six vectors, three maximum values and three minimums. These vectors are tested to find the positions which are in fact farthest from and closest to the datum which served as the starting point for the drift determination. Using the maximum and minimum values obtained in the test as entering arguments, a table[44] stored in memory produced the final value of drift error, d_e. See Figure 10-D.

The final determination of the total probable error of position, c, is then accomplished by combining the three separate errors in accordance with the equation:

$$c = \sqrt{X^2 + Y^2 + d_e^2}$$

See Figure 10-E.

Determination of the limits of the search area.

Once a datum point has been established for a specified time, t_i,

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[44] National Search and Rescue Manual, op. cit., p. 6-9.

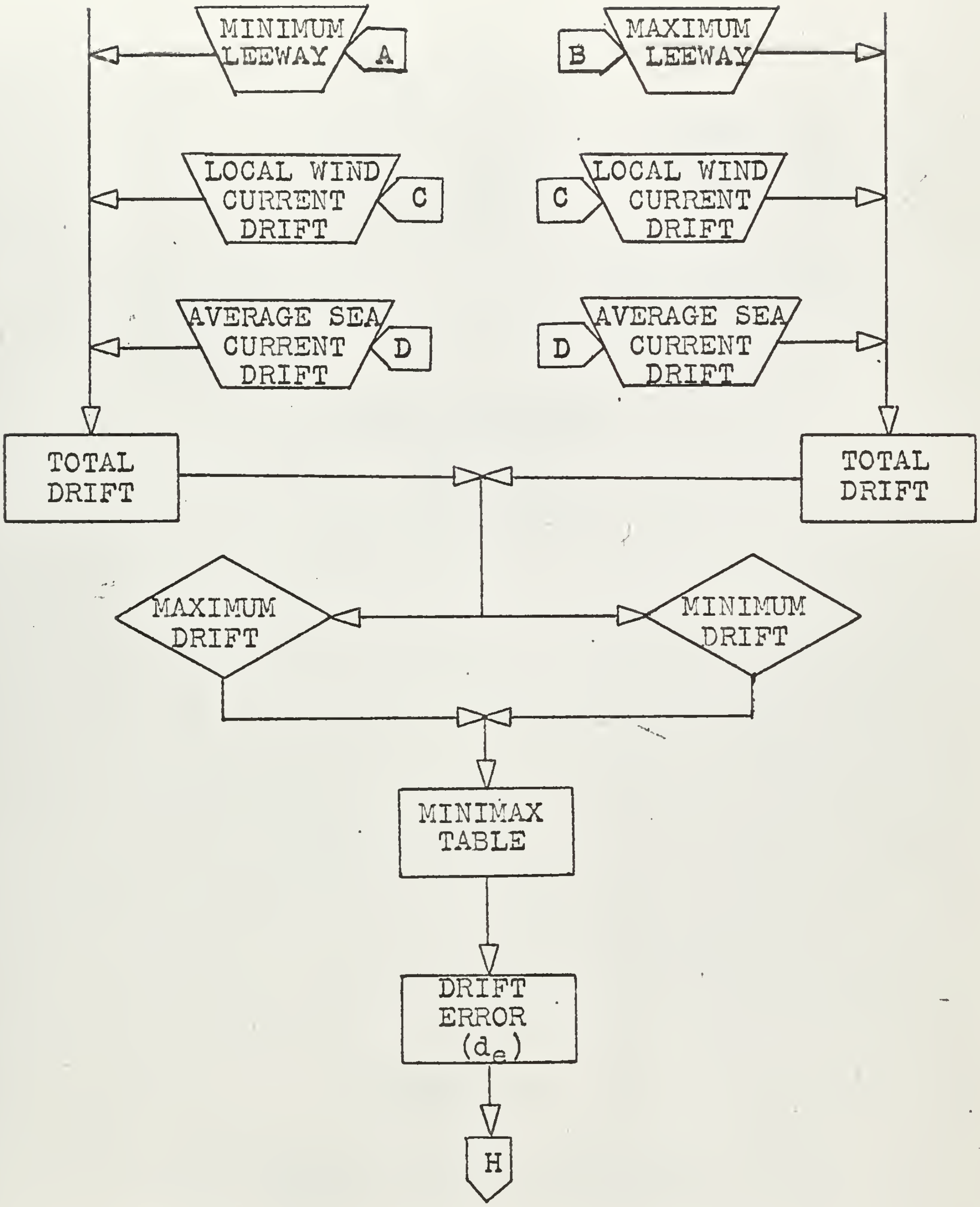

FIGURE 10-D

FLOW DIAGRAM FOR THE DETERMINATION OF DRIFT ERROR, d_e

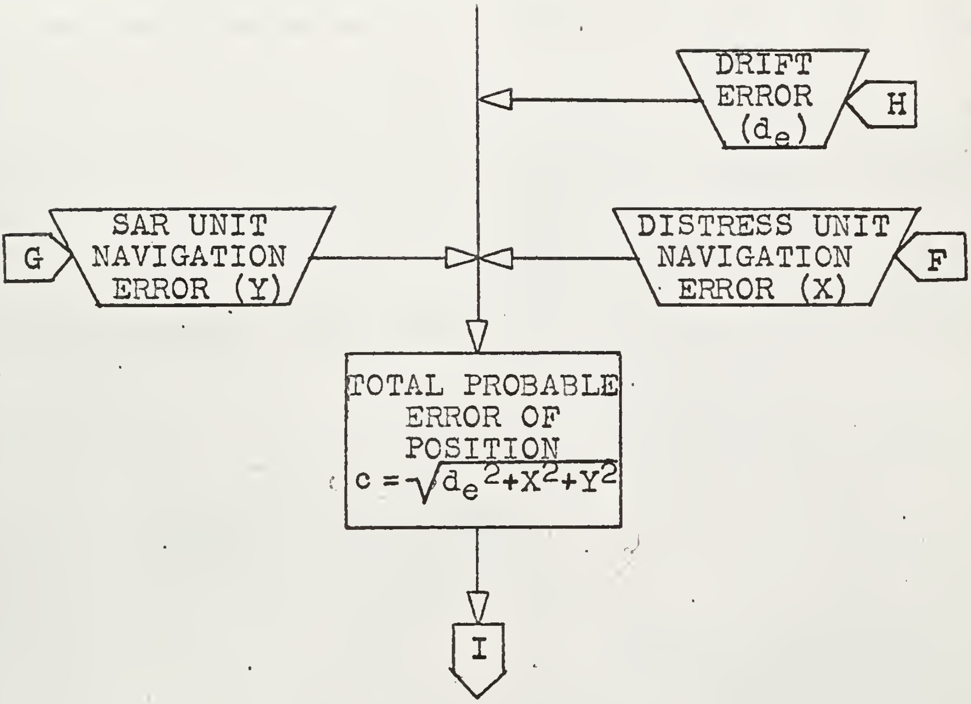
DRIFT ERROR (d_e)
H
SAR UNIT NAVIGATION ERROR (Y)
G
DISTRESS UNIT NAVIGATION ERROR (X)
F
TOTAL PROBABLE ERROR OF POSITION
$c = \sqrt{d_e^2 + X^2 + Y^2}$
I

FIGURE 10-E

FLOW DIAGRAM FOR THE FINAL DETERMINATION OF TOTAL PROBABLE ERROR OF POSITION, c

and the total probable error of the position has been determined, the boundary limits of the search area may be defined. These boundaries may be expressed in either of two ways. The first is in the form of the length of the search radius which extends from the datum point. This method is used for vector type searches. The second is in the form of geographical coordinates of latitude and longitude defining a rectangular search area centered on datum with a length and width each equal to twice the search radius. See Figure 11.

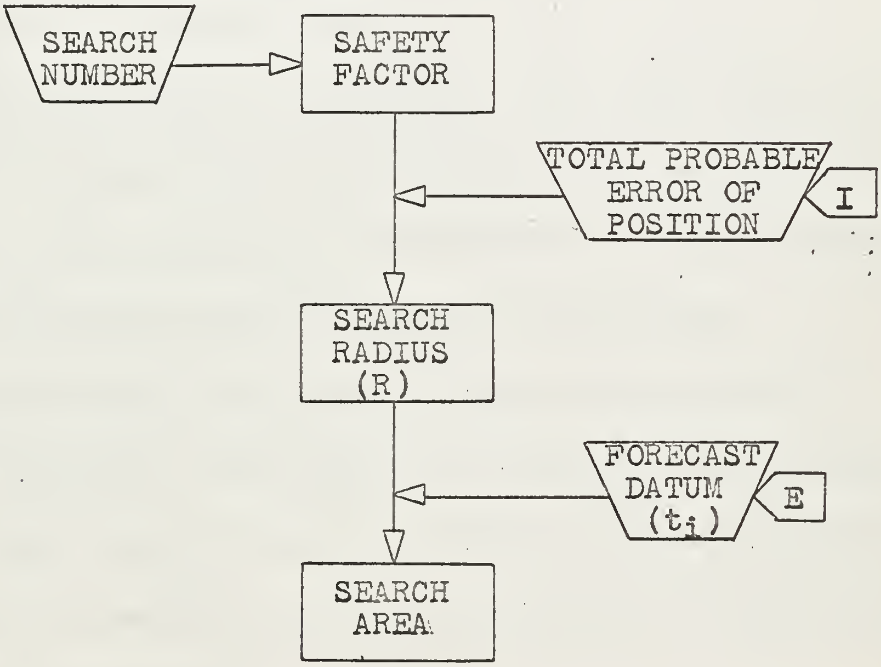

FIGURE 11

FLOW DIAGRAM FOR THE DETERMINATION OF THE SEARCH AREA

The specific input data needed to define the search area is:

1. The number of the search being conducted. This is needed to ascertain what safety factor will be applied in the calculation of the radius, R.

2. The various safety factors associated with each different search number. These are the factors listed in Chapter II, page 29.

3. The total probable error of position, c. This has been computed in the preceding phase.

4. The coordinates of the forecasted datum which were determined in the first phase of the overall program.

The actual computations are fairly simple. The search radius, R, is the product of the safety factor and the total probable error of position, c. This may be printed out along with the coordinates of the forecasted datum to provide the first method of defining the search area.

In the second method, the latitude increment will be equal to the search radius (in nautical miles) divided by 60 nautical miles per degree of latitude. This increment of latitude is added to the forecasted datum latitude to yield the northern limit and subtracted from the datum latitude to provide the southern limit.

In determining the increment of longitude equal to the search radius, the datum latitude was considered to be the middle latitude, L_m, of a

small area Mercator plotting sheet. The equation relating the search radius distance in miles to degrees of longitude is:[45]

$$\text{Degrees of Longitude} = \frac{\text{R miles}}{60\cos L_m \text{ miles}/^\circ \text{ of longitude}}$$

This increment was then subtracted from the datum longitude to obtain the longitude of the eastern limit and was added to the datum longitude for the western limit.

This then completes the basic program for the determination of the search area problem. However, the specific program which was developed contains three additional items of interest. The first two of these are designed to provide general information concerning the possible conditions of the survivors. This information assists the RCC Controller in making the difficult decision of when to terminate an unsuccessful search and rescue case. It will also provide information to the search units indicating tentative survival times.

The first of these two subroutines interrogates a table stored in memory which provides information expressing the effect of wind and air temperatures on exposed survivors. This table converts the values of wind and air temperatures at the scene of the incident to the equivalent temperature on exposed flesh if the wind velocity were zero.[46]

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[45] Bowditch, op. cit., p. 89. This section describes the various mathematical relationships between latitudes, longitudes, and distances on small area Mercator plotting sheets.

[46] This information was obtained from a "Wind Chill Chart" developed by the U.S. Army. It appeared in the December 18, 1964 Commandant's Bulletin, No. 51-64, Supplement No. 4. published by the U.S. Coast Guard. This table was reprinted from U.S.N. Medical Newsletter, Vol. 32, No. 12.

The inputs needed are two in number. First, the air temperature at the scene is needed and may be obtained from weather reports or forecasts for the area. The second input is that of the velocity of the local surface winds in the area. This has been entered in an earlier phase.

These two inputs serve as the entering arguments for the table which then reads out the desired information directly. See Figure 12.

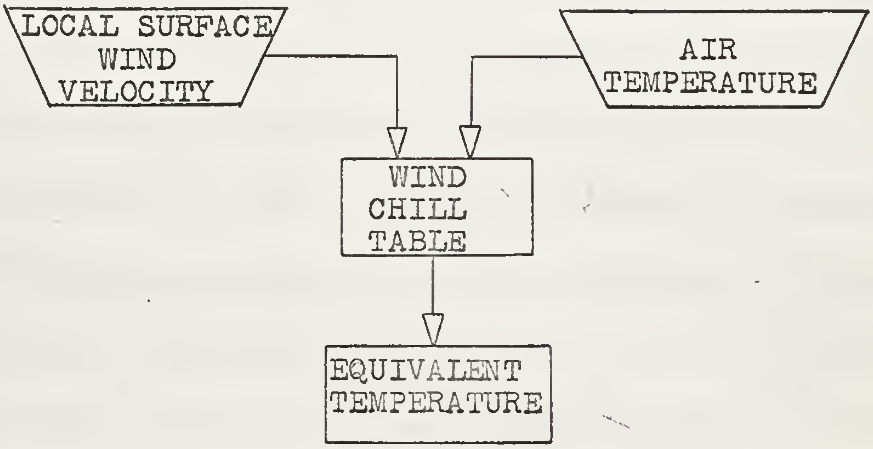

FIGURE 12

GENERAL FLOW DIAGRAM FOR EQUIVALENT TEMPERATURES AT VARIOUS WIND VELOCITIES

The second subroutine associated with the condition of the survivors deals with immersion hypothermia, that is, the life expectancy of survivors immersed in water at different temperatures. The desired information is an estimate of the time survivors will remain conscious and an estimate of the expected time they have before death becomes an almost certainty.

The only input needed for this portion of the program is that of the sea water temperature in the area of the distress incident. This information is also available in the local weather reports or forecasts for the distress area.

This input information is the entering argument into tables which provide the time ranges at different temperatures for consciousness and time until death.[47] See Figure 13.

The third and final item pertains to the format of the final output. In order to expedite the entire process of transmitting information to the search units which may be assigned, the format of the computer printed output was designed to be that of the standard Outgoing Message format. Instead of taking the information from a given computer run, transcribing this information to message blanks, and then routing it to the communications center, the actual print out serves as the drafted message. The only information which must be inserted is the message date-time group (DTG), address or name of search unit involved, identification of the distress incident, and the releasing officer's approval. This also eliminates the possibility of transcription errors in the many numbers involved. Appendix B. contains samples of the print out format for the first and subsequent searches with computer calculated figures indicated by

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[47] Climatological and Oceanographic Atlas for Mariners (Washington: Office of Climatology and Oceanographic Analysis Division, Department of Commerce, 1961), Chart No. 157.

underscoring and RCC Controller entered information indicated by underscored X's (XXX). In the space after the last standard print out paragraph the RCC Controller can enter any additional information that he deems appropriate.

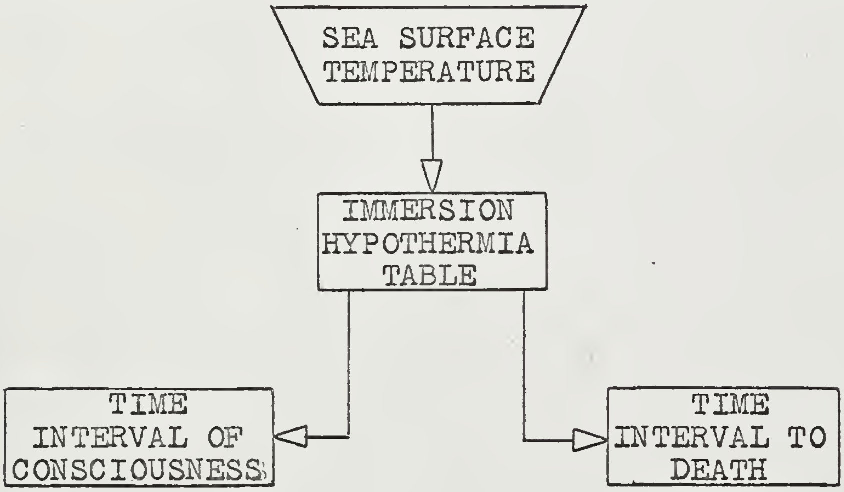

FIGURE 13

FLOW DIAGRAM FOR IMMERSION HYPOTHERMIA

CHAPTER IV

RESULTS

The specific computer program which resulted from this study is found in Appendix B. As each portion of the program was developed, it was tested in such a way that every part of the program was operated. Intermediate print-outs of various steps were obtained and verified for all possible types of inputs for that particular portion. Efforts were directed toward simplifying and shortening the routines involved.

As the final program was amalgamated, the testing and review continued. When it was found to be functioning properly, the various test print-out statements and corresponding comment cards were removed. Only those comment cards which will assist in reviewing the program remain.

Sample illustrations of a distress case involving an aircraft (ditching) with associated survival craft ranging from life jacket, life raft to life boat, with a ship as the search unit are found in the following section. These problems show the input data, the manual solution, and the computer solution. Manual solutions were done on small area plotting sheets. It was noted that when the manual solutions were done by people thoroughly familiar with the problem, human error lead to one 17 mile error in datum. The computer solution was correct.

The running time for the samples varied with the number of the search.

The longest time, 68 seconds, occurred on the run for the initial search, and 54 seconds were required for the subsequent searches. The first search has a longer print-out associated with the distress message. It also involved computations of initial position error of the distress incident and SAR unit navigation error as well as the immersion hypothermia and chill factor relationships which were not computed in subsequent runs. All running times would be reduced if this program were in an operational status as the various tables, program instructions and other associated data would already be in storage within the computer. This information had to be entered at the beginning of each of these sample runs.

I. TRIAL DATA COMPUTATIONS

RUN ONE

INPUT DATA

Classification of distress unit position report	Aircraft - DR
Classification of SAR unit navigation method	Ship - FIX
Initial reported distress position	42.50N, 52.42W
Position of distress unit's last fix	41.50N, 61.50W
SAR unit position at start of case	50.00N, 35.00W
Time of distress incident	301730Z (JAN)
Time specified for arrival of SAR unit	021130Z (FEB)
Surface wind at distress position	340°T @ 17 kts.
Surface wind for past 24 hours at distress position	265°T @ 10 kts.
Average surface current at distress position	195°T @ 15.6 miles/day
Air temperature at distress position	12.8°C
Sea water temperature at distress position	7.2°C
Search number	1
Type lifesaving craft employed	Life raft

RESULTS BY MANUAL COMPUTATIONS

Distress unit navigation error (X)	51.3 miles
SAR unit navigation error (Y)	5.0 miles
Forecast datum of survivors	40.97N, 51.80W
Forecast search area limits	42.14N, 39.81N 50.25W, 53.35W

RESULTS BY COMPUTER (PROGRAM) COMPUTATIONS

Distress unit navigation error (X)	51.1 miles
SAR unit navigation error (Y)	5.0 miles
Forecast datum of survivors	40.90N, 51.84W
Forecast search area limits	42.01N, 39.80N 50.37W, 53.30W

RUN TWO

INPUT DATA

Last computed distress position	40.90N, 51.84W
Type lifesaving craft employed	Man in water
Time associated with last distress position	021130Z (FEB)
Time specified for next search to begin	041330Z (FEB)
Surface wind at computed distress position	180°T @ 20 kts.

Surface wind for past 24 hours at computed distress position	340°T @ 17 kts.
Average surface current at computed distress position	195°T @ 15.6 miles/day
Search number	2

RESULTS BY MANUAL COMPUTATIONS

Forecast datum of survivors	39.88N, 52.16W
Forecast search area limits	41.30N, 38.46N 50.28W, 54.04W

RESULTS BY COMPUTER (PROGRAM) COMPUTATIONS

Forecast datum of survivors	39.88N, 52.14W
Forecast search area limits	41.30N, 38.47N 50.30W, 53.98W

RUN THREE

INPUT DATA

Last computed distress position	39.88N, 52.14W
Type lifesaving craft employed	Life boat
Time associated with last distress position	041330Z (FEB)
Time specified for next search to begin	062130Z (FEB)

Surface wind at computed distress position	095°T @ 04 kts.
Surface wind for past 24 hours at computed distress position	180°T @ 20 kts.
Average surface current at computed distress position	180°T @ 15.6 miles/day
Search number	3

RESULTS BY MANUAL COMPUTATIONS

Forecast datum of survivors	39.89N, 52.09W
Forecast search area limits	41.62N, 38.16N 49.83W, 54.35W

RESULTS BY COMPUTER (PROGRAM) COMPUTATIONS

Forecast datum of survivors	39.87N, 52.07W
Forecast search area limits	41.60N, 38.14N 49.82W, 54.32W

SUMMARY OF RUNNING TIMES

Run number one	1 min. 8 sec.
Run number two	0 min. 54 sec.
Run number three	0 min. 54 sec.

CHAPTER V

SUMMARY AND CONCLUSIONS

I. SUMMARY

Growing maritime operations have found the need for more effective search and rescue facilities expanding. One area of search and rescue operations, that of the determination of search areas and datum points, has been studied to ascertain the feasibility of the use of computers in solving this problem. Using the *National Search and Rescue Manual* as a guide to the present doctrine employed by this country, a computer program was developed, tested and found to be an operationally feasible program.

During the course of the development of this program certain areas of the current doctrine were reviewed in the light of recent literature and theories which may offer improved techniques. The conclusions reached in this review are discussed in the following section.

II. CONCLUSIONS

The basic doctrine outlined in the *National Search and Rescue Manual* is amenable to computer programming. Although the program which was developed does not cover every possible aspect of this doctrine, it does

handle one of the basic types of search problems frequently encountered. This program can greatly reduce the time required to solve the problem associated with the location of datum and its surrounding search area. The accuracy of the computer solution is dependent entirely upon the accuracy of the input information. It greatly reduces the possibilities of human error in carrying out the rather extensive calculations involved in the problem. As new methods are developed for determining various portions of the input data with greater accuracy, the value of the computer solution will greatly increase.

In working with the National Search and Rescue Manual certain conclusions were reached. The first of these was that the doctrine outlined, although not the ultimate in sophistication, certainly represented an excellent model for use in existing RCC facilities which were not equipped with automatic data processing equipment or with large staffs. Admittedly there were areas of weakness in the basic doctrine. However, to refine the doctrine to fully consider the different shortcomings would have unnecessarily complicated the problems at the sacrifice of valuable time. And there is no definite measure of how this additional refinment would alter the risks associated with the resultant decisions.

However, the review of the literature in this study did suggest several possible areas for improvement if a computer installation is available, and one suggestion is applicable with existing manual operations.

Considering the computer applications first, it is apparent that the problem of free fall and parachute drift is subject to operational analysis by computers. The present running time of slightly less than ten minutes associated with Cohan's program can probably be reduced as his program is refined.

Also, a computer could use the program developed by Burns at the Navy Oceanographic Office to determine a drift elipse area based upon the statistical current roses found in the Atlas of Surface Currents.

The development by the Fleet Numerical Weather Facility of the system for forecasting surface currents appears to have the greatest potential for improving present doctrine in that it may be used either with or without a computer. The program developed by this study can be modified to receive information from the Fleet Numerical Weather Facility on the predicted surface currents at the four points of the grid containing datum. These vectors, which reflect a combination of the permanent circulation pattern and local wind currents, can then be resolved into a vector for the datum point. Since this information is based on recently reported weather conditions and sea surface temperatures, it should tend to be more accurate than the information taken from the Atlas of Surface Currents which represents a statistical summary of many years based, in some cases, on a single observation.

This analysis of Fleet Numerical Weather Facility information could also be graphically determined or manually calculated without the assistance

of a computer.

Laevastu's work indicates that local wind current divergence can be treated in a more refined manner by considering small increments of latitude and wind velocities. This refinement could be handled very easily by modifying that portion of the specific program relating to this computation.

III. IMPLICATIONS

The program developed in this study can be rewritten in the computer language used in the AMVER Center, Office of the Commander Eastern Area. Thus, it can serve to assist the handling of these distress cases which occur in the North Atlantic. It is suggested that serious consideration be given to the adaptation of the Fleet Numerical Weather Facility data services and the associated modification of this basic program. Should this latter suggestion not be practical, consideration should be directed toward utilizing Burns' program in conjunction with the Atlas of Surface Currents. As the Pacific AMVER system becomes fully operational, this this program can be further modified to handle SAR cases falling under the jurisdiction of Commander Western Area.

In view of the number of entries found in the Atlas of Surface Currents (approximately 20,000 for the Atlantic and 40,000 for the Pacific) it is not recommended that this information be placed in storage and the basic

program modified to handle that portion of the Average Sea Current problem automatically. Individual cases should continue to use this information as manually extracted from the appropriate charts.

IV. RECOMMENDATION OF AREAS FOR FURTHER STUDY

This study has served as a first step in the development of a full-scale computerized SAR program. As such, it has opened up many new areas where further study and research should prove fruitful. Some of these areas are discussed briefly below.

Determination of a datum and associated search area when the time of the incident and estimated position are not known.

When a ship or aircraft is missing or overdue, the RCC Controller is faced with the problem of estimating the probable boundaries of an area in which the distress may have occurred. He must establish the limits of the time period in which the distress could have occurred. With this information he then applies minimum and maximum possible values of drift for the time period in question starting with the earliest possible distress time and ending with the latest possible distress time.

Development of a fully operational free fall and parachute drift program.

Refinement and further development of the work done by Armacost,

Saunders and Cohan can materially contribute to the effectiveness of a computer program for SAR operations.

Development of a program to handle small craft (inshore) distress cases.

With the increasing interest in recreational boating displayed by the general public, it is mandatory that improved techniques be developed to handle the associated increase in SAR cases occurring with these craft. It has been estimated that approximately 85% of all SAR cases handled by the U. S. Coast Guard occur within twenty to twenty-five miles of the coast. Someplace in the neighborhood of 95% of all cases are found to take place within 100 miles of the coastline. [48]

One of the major difficulties in treating these cases is associated with the effects of tidal currents, rotary currents, and run-off currents, all of which are effected by the configuration of the coastline.

Development of a program relating search area, search units, and search patterns.

Once a search area has been specified, the RCC Controller is faced with the problem of recommending search patterns for those available

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[48] B. R. House, Analysis of U. S. Coast Guard Aviation Operations (Report Number SER-50371, Stratford: Sikorsky Aircraft Division of United Aircraft Corporation, 1964), p. 36.

search units which are participating in the case. Since the type of search pattern recommended is a function of the number and type of search units participating, the weather and other operating conditions at the scene, and the various probabilities of detection desired, the development of a program to assist in making this recommendation would be most beneficial. In essence this would be a program treating the doctrine outlined in Chapter Seven of the National Search and Rescue Manual.

Studies evaluating the frequency of distress cases and the location of SAR facilities.

As the new system of reports for distress cases becomes fully operational, actual historical data will become available. Analysis of this data and existing SAR facilities should shed new light on possible relocation and expansion of SAR facilities. Studies similar to that performed by DuPeza, Eustis, Guthrie and Zook[49] should be of great value.

Continued drift analysis.

At the present time the U. S. Coast Guard has a drift datum marker buoy which is being evaluated by operational field testing. The data obtained from these tests coupled with the current studies being conducted

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[49] Jules B. DuPeza and others, "A Method for Evaluating SAR Requirements for the Twelfth Coast Guard District" (Unpublished Master's research paper, The United States Naval Postgraduate School, Monterey, 1964).

by the U. S. Naval Oceanographic Office, U. S. Naval Fleet Numerical Weather Facility, and other oceanographers should provide a great deal of information which can lead to a better understanding of the problems associated with ocean current analysis.

In all cases, the continued application of man's growing knowledge and utilization of the tools which he has developed can be directed toward the benefit of mankind. The success or failure of such efforts is limited only by the imagination, enthusiasm and patience of those who truly seek the answers.

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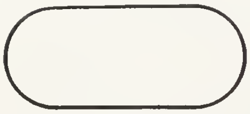
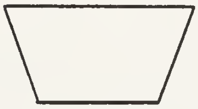
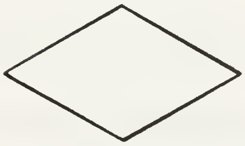
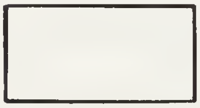
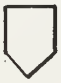
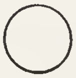
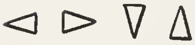
APPENDIX A.

FLOWCHART SYMBOLS AND DEFINITIONS

FLOWCHART SYMBOLS AND DEFINITIONS

	- Terminal indicator
	- Input/output indicator
	- Decision indicator
	- Processing, annotating indicator
	- Off page connector
	- On page connector
	- Flow indicator

APPENDIX B.

PROGRAM SAR

Program SAR is the specific program developed in this study. It determines the datum point and associated search areas for distress cases involving ships and aircraft which ditch. This Appendix includes the definitions of the terms and inputs found in the program, the associated computer program itself, and sample print-out as discussed at the end of Chapter III.

DEFINITIONS OF ALL INPUT VARIABLES

VARIABLE NAME	DEFINITION
ATEM	Air temperature at distressed position in degrees centigrade (°C).
CRAFT	Type lifesaving craft that RCC Controller thinks survivors will employ: Life jacket - code 1. Boat - code 2. Raft - code 3.
DCLS	Classification of Distressed unit's position report: Surface DR - code 01 Aircraft DR - code 02 Surface FIX - code 05 Aircraft FIX - code 10 Surface and Aircraft DF Class A - code 05 Class B - code 20 Class C - code 50 Surface and Aircraft DF-FCC Class A - code 20 Class B - code 40 Class C - code 60 Class D - code 80
DDATE	Date of distress in ZULU (GMT) time.
DFTERR	Drift error from Min-Max Table in CG-308.
DHR	Hour of distress in ZULU (GMT) time.
DLAT	Latitude of distress in degrees and hundredths.
DLONG	Longitude of distress in degrees and hundredths.
DMIN	Minute of distress in ZULU (GMT) time.
DMO	Number of days in the month associated with DDATE.

DROG	Drift of a raft or boat without a drogue as a factor of wind velocity. Values obtained from a graph in CG-308.
EXH	Time until an immersed man will become exhausted or unconscious as a factor of sea water temperature. Obtained from table in *Atlas of Surface Currents*.
FLAT	Latitude of last fix of distressed unit in degrees and hundredths.
M	Number of the search that is being computed.
PWDIR	Wind direction at the distress position for the 24 hour period prior to the distress.
PWIND	Wind velocity at the distress position for the 24 hour period prior to the distress.
SCLS	Classification of the SAR unit's position determination: Surface DR - code 03 Aircraft DR - code 04 Surface FIX - code 05 Aircraft FIX - code 10 Surface and Aircraft DF Class A - code 05 Class B - code 20 Class C - code 50 Surface and Aircraft DF-FCC Class A - code 20 Class B - code 40 Class C - code 60 Class D - code 80
SCURD	Direction of surface current at distress position taken from the *Atlas of Surface Currents*.
SCURV	Velocity of surface current at distress position taken from the *Atlas of Surface Currents*.
SDATE	Date specified by RCC Controller, usually the ETA of the SAR unit on scene in ZULU (GMT) time.
SEARCH	Safety factor associated with 'M'.

SHR	Hour specified by RCC Controller, usually the ETA of the SAR unit on scene in ZULU (GMT) time.
SLAT	Latitude of the SAR unit's last fix in degrees and hundredths.
SLOW	Longitude of the SAR unit's last fix in degrees and hundredths.
SMIN	Minute specified by the RCC Controller, usually the ETA of the SAR unit on scene.
STEMP	Temperature of the seawater at the distress position, °C.
STM	Survival time for a man immersed in water at a certain temperature as a factor of the temperature.
WDIR	Wind direction at distress position in degrees True.
WIND	Velocity of wind at distress position.
WINTEM	Wind chill factor for the effect of wind on exposed flesh.
X	Position error for the distress report.
Y	Position error for the SAR unit.

INPUT DATA FOR FIRST SEARCH

VARIABLE NAME	DATA CARD COLUMNS	SOURCE AND FORMAT OF INPUT DATA
DCLS	1, 2	Classification of distressed unit's position report. Two digit code number.
SCLS	3, 4	Classification of search unit's position report. Two digit code number.
DLAT	5-10	Latitude of distress incident. Six digit number of degrees and hundredths (i.e. 45°39' = 045.65).
DLONG	11-16	Longitude of distress incident. Six digit number of degrees and hundredths (i.e. 75°21'= 075.35).
FLAT	17-22	Latitude of last fix of distressed unit six digit number of degrees and hundredths. (i.e. 42°54'= 042.90).
FLON	23-28	Longitude of last fix of distressed unit. Six digit number of degrees and hundredths (i.e. 63°13'= 063.22).
SLAT	29-34	Latitude of SAR unit at start of incident. Six digit number in degrees and hundredths (i.e. 40°38'= 040.63).
SLON	35-40	Longitude of SAR unit at start of incident. Six digit number in degrees and hundredths (i.e. 68°07'= 068.12).
CRAFT	41, 42	Type of life saving device that the RCC coordinator believes survivors will be using. One digit code number followed by a decimal.
DDATE	43, 44	Date of distress incident. Two digit number from the distress DTG.
DHR	45, 46	Hour of the distress incident. Two digit number from the distress DTG.

VARIABLE NAME	DATA CARD COLUMNS	SOURCE AND FORMAT OF INPUT DATA
DMIN	47, 48	Minute of the distress incident. Two digit number from the distress DTG.
SDATE	49, 50	Date specified by the RCC Controller, usually the date (GMT) that the SAR unit will arrive on scene. Two digit number.
SHR	51, 52	Hour specified by the RCC Controller, usually the hour (GMT) that the SAR unit will arrive on scene. Two digit number.
SMIN	53, 54	Minute specified by the RCC Controller, usually the minute that the SAR unit will arrive on scene. Two digit number.
WIND	55, 56	Wind velocity at distress position from the latest weather information. Two digit number.
PWIND	57, 58	Wind velocity for the previous 24 hours at the distress position. Two digit number.
WDIR	59-61	Direction from which the wind is blowing at the distress position at time of distress. Three digit number.
PWDIR	62-64	Direction from which the wind had been blowing at the distress position for the 24 hour period prior to the distress time. Three digit number.
SCURV	65-68	Surface current velocity at the distress position taken from the *Atlas of Surface Currents*. Four digit number (nautical miles per day) in miles and tenths (i.e. 09.9).
SCURD	69-71	Direction of the surface current flow at the distress position taken from the *Atlas of Surface Currents*. Three digit number.

VARIABLE NAME	DATA CARD COLUMNS	SOURCE AND FORMAT OF INPUT DATA
ATEM	72-75	Air temperature at the distressed position at the distress time taken from weather reports in degrees centigrade. Four digit number in degrees and tenths (i.e. 17.6).
STEMP	76-79	Sea water temperature at distress position in degrees centigrade taken from latest weather data. Four digit number in degrees and tenths (i.e. 15.3).
M	80	Search number for which datum is to be computed. One digit number.
DMO	1, 2	Number of days in the month of DDATE. Two digit number.
X	3-7	Left blank for the first search.
Y	8-12	Left blank for first search.

INPUT DATA FOR SECOND THRU FIFTH SEARCHES

VARIABLE NAME	DATA CARD COLUMNS	SOURCE AND FORMAT OF INPUT DATA
DCLS	1, 2	Blank.
SCLS	3, 4	Blank.
DLAT	5-10	DTMLAT from preceding search results. Six digit number in same format as DTMLAT.
DLONG	11-16	DTMLONG from preceding search results. Six digit number in same format as DTMLONG.
FLAT	17-22	Blank.
FLON	23-28	Blank.
SLAT	29-34	Blank.
SLON	35-40	Blank.
CRAFT	41, 42	Same as CRAFT in preceding search.
DDATE	43, 44	SDATE from preceding search.
DHR	45-46	SHR from preceding search.
DMIN	47, 48	SMIN from preceding search.
SDATE	49, 50	New specified date by RCC Controller, usually the estimated date (GMT) that the SAR unit will complete the preceding search.
SHR	51, 52	New specified hour by the RCC Controller, usually the estimated hour (GMT) that the SAR unit will complete the preceding search.
SMIN	53, 54	New specified minute by the RCC Controller, usually the estimated minute (GMT)that the SAR unit will complete the preceding search.

VARIABLE NAME	DATA CARD COLUMNS	SOURCE AND FORMAT OF INPUT DATA
WIND	55, 56	Wind velocity at the preceding computed datum position. Taken from weather reports for the preceding specified time (SDATE, SHR, SMIN). Two digits in same format as search one.
PWIND	57, 58	Wind velocity for the previous 24 hours period at datum computed in the preceding run. Two digit number obtained from weather reports.
WDIR	59-61	Wind direction at datum computed in the preceding run. Three digit number obtained from the latest weather report.
PWDIR	62-64	Direction of previous 24 hour wind at datum computed in preceding run. Three digit number obtained from weather reports.
SCURV	65-68	Surface current velocity at datum computed in preceding run. Four digit number of miles and tenths (i.e. 13.4) obtained from the Atlas of Surface Currents.
SCURD	69-71	Direction of surface current at datum computed in preceding run. Three digit number obtained from Atlas of Surface Currents.
ATEM	72-75	Blank.
STEMP	76-79	Blank.
M	80	Number of the search, 2 thru 5. One digit.
DMO	1, 2	Number of days in the month of DDATE. Two digit number.
X	3-7	Value of 'X' from the initial search. Five digit number with one decimal place.
Y	8-12	Value of 'Y' from the initial search. Five digit number with one decimal place.

FIRST SEARCH PRINT OUT

X XXXXXX Z

FM COMEASTAREA

TO XXXXXXXXXXXXXXXXXXXXXX

$\overline{\text{BT}}$

UNCLASS

A. DISTRESSED XXXXXXXXXXXXXXXX

1. FORECAST DATUM AT 021130Z. 40.90N, 51.84W.
2. FORECAST SEARCH AREA BOUNDED BY 42.01N, 39.80N, 50.37W, 53.30W.
3. SURVIVOR CONDITION FROM 301730Z OF MAN IN WATER. TIME UNTIL EXHAUSTION 1.00 HOURS. TIME UNTIL DEATH 3.00 HOURS.
4. EFFECT OF SURFACE WIND SAME AS -27.0 DEGREES FAHRENHEIT WITH ZERO WIND.
5.

$\overline{\text{BT}}$

RELEASED BY XXXXXXXXXXXXXXXXXXXXX

SUBSEQUENT SEARCH PRINT OUT

X XXXXXX Z

FM COMEASTAREA

TO XXXXXXXXXXXXXXXXXXXXXX

BT

UNCLASS

A. DISTRESSED XXXXXXXXXXXXXXXXXX

1. FORECAST DATUM AT 062130Z. 39.87N, 52.07W.
2. FORECAST SEARCH AREA BOUNDED BY 41.60N, 38.14N, 49.82W, 54.32W.

BT

RELEASED BY XXXXXXXXXXXXXXXXXXXXX

```
      PROGRAM SAR
  410 DIMENSION DROG(33)
  411 READ 412, (DROG(N),N=1,33)
  412 FORMAT (18F4.1/ 15F4.1)
 1410 DIMENSION DFTERR(15,15)
 1411 READ 1412,((DFTERR(I,J),J=1,15),I=1,15)
 1412 FORMAT (15F2.0)
  601 DIMENSION SEARCH(5)
  800 READ 801,(SEARCH(K),K=1,5)
  801 FORMAT(5F3.1)
      DIMENSION WINTEM(14,11)
   10 READ 15,  ((WINTEM(I,J),J=1,11),I=1,14)
   15 FORMAT (11F6.1)
      DIMENSION EXH(7),STM(7)
      READ 900,(EXH(I),STM(I),I=1,7)
```

```
  900 FORMAT (12F6.2/2F6.2)
 30000READ 3001,DCLS,SCLS,DLAT,DLONG,FLAT,FLON,SLAT,SLON,CRAFT,DDATE,
     1DHR,DMIN,SDATE,SHR,SMIN,WIND,PWIND,WDIR,PWDIR,SCURV,SCURD,ATEM,
     2STEMP,M,DMO,X,Y
 3001 FORMAT(2F2.0,6F6.2,9F2.0,2F3.0,F4.1,F3.0,2F4.1,I1/F2.0,2F5.1)
      IF(M-1)100,100,403
C     STATEMENTS NUMBER 100 THROUGH 114 COMPUTE THE VALUES OF DISTRESS
C     UNIT NAVIGATION ERROR (X) AND SAR UNIT NAVIGATION ERROR (Y).
  100 IF(DCLS-2.)101,101,102
  101 CLS=DCLS
      ZLAT=FLAT
      ZLON=FLON
      GO TO 197
  102 X=DCLS
  105 IF(SCLS-4.)103,103,104
  103 CLS=SCLS
      ZLAT=SLAT
      ZLON=SLON
```

```
      GO TO 197
  104 Y=SCLS
      GO TO 403
C     STATEMENTS NUMBER 197 TO 107 COMPUTE DISTANCE FROM TWO POSITIONS
C     BY MERIDIONAL PARTS COMPUTATIONS.
  197 DIFLO=60.*ABSF(DLONG-ZLON)
      DIFLA=60.*ABSF(DLAT-ZLAT)
      ANGDL=(45.+DLAT/2.)*3.1416/180.
      ANGZL=(45.+ZLAT/2.)*3.1416/180.
      TANDL=ABSF(SINF(ANGDL)/COSF(ANGDL))
      TANZL=ABSF(SINF(ANGZL)/COSF(ANGZL))
      FTANDL=0.43429*LOGF(TANDL)
      FTANZL=0.43429*LOGF(TANZL)
      DLATM=7915.7*FTANDL-23.2689*SINF(DLAT*3.1416/180.)
      ZLATM=7915.7*FTANZL-23.2689*SINF(ZLAT*3.1416/180.)
      DIFM=ABSF(DLATM-ZLATM)
      TANCE=DIFLO/DIFM
      CE=ATANF(TANCE)
```

```
  107 IF(CLS-0.)108,108,109
  108 STOP 5
  109 IF(CLS-3.)110,113,114
  110 IF(CLS-2.)111,112,403
  111 X=5.+.05*DIFLA/COSF(CE)
      GO TO 105
  112 X=10.+.1*DIFLA/COSF(CE)
      GO TO 105
  113 Y=5.+.05*DIFLA/COSF(CE)
      GO TO 403
  114 Y=10.+.1*DIFLA/COSF(CE)
C     STATEMENTS NUMBER 403 THROUGH 405 COMPUTE THE NUMBER OF HOURS THAT
C     THE DISTRESS POSITION IS TO BE PROJECTED AHEAD.
  403 DHRS=DHR+DMIN/60.
  404 SHRS=SHR+SMIN/60.
  700 IF(DDATE-SDATE)405,405,701
  701 TIME=(DMO-DDATE+SDATE)*24.-DHRS+SHRS
  702 GO TO 406
```

```
  405 TIME=((SDATE-DDATE)*24.)-DHRS+SHRS
  406 IF(CRAFT-2.)428,407,407
C       STATEMENTS NUMBER 407 THROUGH 427 COMPUTE THE X AND Y COMPONENTS
C       OF LEEWAY.
  407 IF(WIND-5.)408,408,409
  408 DLEE=.8*WIND/24.
      GO TO 413
  409 DLEE=((WIND+2.5)/1.87)/24.
  413 NWIND=WIND
      IF(NWIND-33)414,414,4000
 4000 NWIND=33
  414 WDLEE=DROG(NWIND)/24.
  415 DIMENSION XMAX(3),XMIN(3),YMAX(3),YMIN(3)
  416 WDIR=WDIR+260.
  417 DO 427 N=1,3
  418 WDIR=WDIR-40.
  419 WRAD=WDIR*3.1416/180.
  420 RADI=5.*3.1416/2.-WRAD
```

```
 421 YMIN(N)=DLEE*SINF(RADI)*TIME
 422 YMAX(N)=WDLEE*SINF(RADI)*TIME
 423 XMIN(N)=DLEE*COSF(RADI)*TIME
 424 XMAX(N)=WDLEE*COSF(RADI)*TIME
 427 CONTINUE
1427 WDIR=WDIR-140.
C      STATEMENTS NUMBER 428 THROUGH 434 COMPUTE THE X AND Y COMPONENTS
C      OF LOCAL WIND CURRENT DRIFT.
 428 WCUR=(PWIND/1.18)/24.
 429 IF(DLAT-10.)430,430,432
 430 WCURD=PWDIR+180.
2430 IF(WCURD-360.)433,433,2431
2431 WCURD=WCURD-360.
2432 GO TO 2430
 432 WCURD=PWDIR+210.
1432 GO TO 2430
 433 XCUR=WCUR*COSF(5.*3.1416/2.-(WCURD*3.1416/180.))*TIME
 434 YCUR=WCUR*SINF(5.*3.1416/2.-(WCURD*3.1416/180.))*TIME
```

```
C      STATEMENTS NUMBER 452 THROUGH 455 COMPUTE THE X AND Y COMPONENTS
C      OF AVERAGE SURFACE CURRENT DRIFT.
  452 IF(SCURV)453,457,454
  453 STOP 1
  454 YSCUR=SCURV/24.*SINF(7.854-SCURD*3.1416/180.)*TIME
  455 XSCUR=SCURV/24.*COSF(7.854-SCURD*3.1416/180.)*TIME
  4570DIMENSION DRIFT(6),DFTMAX(3),DFTMIN(3),XDRMAX(3),XDRMIN(3),
     1YDRMAX(3), YDRMIN(3)
C      STATEMENTS NUMBER 458 THROUGH 470 COMPUTE TOTAL MAXIMUM AND
C      MINIMUM COMPONENTS OF DRIFT .
  458 DO 465 N=1,3
  459 XDRMAX(N)=XSCUR+XCUR+XMAX(N)
  460 XDRMIN(N)=XSCUR+XCUR+XMIN(N)
  461 YDRMAX(N)=YSCUR+YCUR+YMAX(N)
  462 YDRMIN(N)=YSCUR+YCUR+YMIN(N)
  463 DFTMAX(N)=SQRTF(XDRMAX(N)**2+YDRMAX(N)**2)
  464 DFTMIN(N)=SQRTF(XDRMIN(N)**2+YDRMIN(N)**2)
      DRIFT(N)=DFTMAX(N)
```

```
      DRIFT(N+3)=DFTMIN(N)
  465 CONTINUE
      IF(CRAFT-2.)466,466,1466
 1466 IF(DRIFT(2)-DRIFT(5))2466,3466,3466
 2466 DFTMX=DRIFT(5)
      DFTMN=DRIFT(2)
      GO TO 474
 3466 DFTMX=DRIFT(2)
      DFTMN=DRIFT(5)
      GO TO 474
  466 DFTMX=DRIFT(1)
      DO 468 N=2,6
      IF(DFTMX-DRIFT(N))467,468,468
  467 DFTMX=DRIFT(N)
  468 CONTINUE
      DFTMN=DRIFT(1)
      DO 470 N=2,6
      IF(DFTMN-DRIFT(N))470,469,469
```

```
  469 DFTMN=DRIFT(N)
  470 CONTINUE
C     STATEMENTS NUMBER 474 THROUGH 478 COMPUTE THE VALUE OF MINIMAX
C     DRIFT ERROR (DE).
  474 I=(DFTMX+10.)/10.
  476 J= DFTMN/10.
  477 IF(J) 2478,2478,478
 2478 J=1
  478 DE=DFTERR(I,J)
C     STATEMENTS NUMBER 500 THROUGH 503 COMPUTE PROJECTED LATITUDE OF
C     DATUM.
  500 XDATUM=(XDRMAX(2)-XDRMIN(2))/2.+XDRMIN(2)
  501 YDATUM=(YDRMAX(2)-YDRMIN(2))/2.+YDRMIN(2)
  502 DISTDTM=SQRTF(XDATUM**2+YDATUM**2)
  503 DTMLAT=DLAT+(YDATUM/60.)
C     STATEMENTS NUMBER 504 THROUGH 515 COMPUTE PROJECTED LONGITUDE OF
C     DATUM.
  504 ANGDL=(45.0+DLAT/2.0)*3.1416/180.
```

```
505 ANGDTML=(45.0+DTMLAT/2.0)*3.1416/180.
506 TANDL=0.43429*LOGF(ABSF(SINF(ANGDL)/COSF(ANGDL)))
507 TANDTML=0.43429*LOGF(ABSF(SINF(ANGDTML)/COSF(ANGDTML)))
508 DLATM=7915.7*TANDL-23.2689*SINF(DLAT*3.1416/180.)
509 DTMLM=7915.7*TANDTML-23.2689*SINF(DTMLAT*3.1416/180.)
510 DIFDM=ABSF(DLATM-DTMLM)
511 DTMDLO=DIFDM*DISTDTM*ABSF((SQRTF(1.-(YDATUM/DISTDTM)**2))/YDATUM)
512 IF(XDATUM)513,514,515
513 DTMLONG =DLONG+DTMDLO/60.
    GO TO 600
514 DTMLONG=DLONG
    GO TO 600
515 DTMLONG =DLONG-DTMDLO/60.
C   STATEMENT NUMBER 600 COMPUTES TOTAL PROBABLE ERROR OF POSITION (C).
600 C=SQRTF(X**2+Y**2+DE**2)
C   STATEMENT NUMBER 602 COMPUTES SEARCH RADIUS (R).
602 R=SEARCH(M)*C
C   STATEMENTS NUMBER 603 THROUGH 607 COMPUTE SEARCH AREA LIMITS.
```

```
603 ANLAT=DTMLAT+R/60.
604 SLAT=DTMLAT-R/60.
605 DFLONG=(R/COSF(DTMLAT*3.1416/180.))/60.
606 ELONG=DTMLONG-DFLONG
607 WLONG=DTMLONG+DFLONG
    IF(M-1)26,26,608
C   STATEMENTS NUMBER 26 THROUGH 48 COMPUTE THE WIND CHILL FACTOR.
 26 CFORWIN=1.13*WIND
 27 IF(CFORWIN-45.00)28, 32, 32
 28 DO 30 J=1,11
 29 IF(CFORWIN-WINTEM(1,J))40,40,30
 30 CONTINUE
 32 J=11
 40 CFORTEM=ATEM*9./5.+32.
 42 DO 48 I=2,14
 44 IF(CFORTEM-WINTEM(I,J))48,50,50
 48 CONTINUE
C   STATEMENTS NUMBER 50 THROUGH 906 COMPUTE IMMERSION HYPOTHERMIA.
```

```
 50 STEMP=STEMP*9./5.+32.
    IF(STEMP-32.5)902,902,903
902 K=1
    GO TO 907
903 TEMP=80.
    DO 904 K=1,6
    IF(STEMP-TEMP)905,906,906
905 TEMP=TEMP-10.
904 CONTINUE
906 K=8-K
608 KDTG=(SDATE*10000.)+(SHR*100.)+SMIN
609 JDTG=(DDATE*10000.)+(DHR*100.)+DMIN
    IF(M-1)907,907,909
907 PRINT 908,KDTG,DTMLAT,DTMLONG,ANLAT,SLAT,ELONG,WLONG,JDTG,EXH(K),
   1STM(K),WINTEM(I,1),DTMLAT,DTMLONG,X,Y
908 FORMAT(//,18X,1HZ,//,6X,14HFM COMEASTAREA,//,6X,2HTO,//,6X,2HBT,//
   16X,7HUNCLASS,//,6X,13HA. DISTRESSED,//,9X,20H1. FORCAST DATUM AT ,
   2I6,2HZ.,F7.2,2HN,,F7.2,2HW.,//,9X,33H2. FORCAST SEARCH AREA BOUNDE
```

```
   3D BY,F7.2,2HN,,F7.2,2HN,,F7.2,2HW,,//12X,F6.2,2HW.,//9X,27H3. SURV
   4IVOR CONDITION FROM ,I6,   29HZ OF MAN IN WATER. TIME UNTIL,//12X,
   510HEXHAUSTION,F7.2,25H HOURS.  TIME UNTIL DEATH,F7.2,7H HOURS.,//,
   69X,33H4. EFFECT OF SURFACE WIND SAME AS,F7.1,19H DEGREES FAHRENHEI
   7T,//,12X,15HWITH ZERO WIND.,//,9X,2H5.,//////,6X,2HBT,/////,6X,
   811HRELEASED BY,///,5X,8HDTMLAT =,F7.2,//,5X,9HDTMLONG =,F7.2,//,
   95X,3HX =,F5.1,//,5X,3HY =,F5.1)
    GO TO 999
909 PRINT 910,KDTG,DTMLAT,DTMLONG,ANLAT,SLAT,ELONG,WLONG,DTMLAT,
   1DTMLONG,X,Y
910 FORMAT(//,18X,1HZ,//,6X,14HFM COMEASTAREA,//,6X,2HTO,//,6X,2HBT,//
   16X,7HUNCLASS,//,6X,13HA. DISTRESSED,//,9X,20H1. FORCAST DATUM AT ,
   2I6,2HZ.,F7.2,2HN,,F7.2,2HW.,//,9X,33H2. FORCAST SEARCH AREA BOUNDE
   3D BY,F7.2,2HN,,F7.2,2HN,,F7.2,2HW,,//12X,F6.2,2HW.,//////,6X,2HBT,
   4/////,6X,11HRELEASED BY,///,5X,8HDTMLAT =,F7.2,//,5X,9HDTMLONG =,
   5F7.2,//,5X,3HX =,F5.1,//,5X,3HY =,F5.1)
999 STOP
    END
```

APPENDIX C

"Parachute Drift"

This Appendix is an extract from the study, "Computer Program of USCG Search and Rescue Procedures," which was an unpublished undergraduate study performed by Cadets First Class Robert L. Armacost and Norman T. Saunders at the United States Coast Guard Academy, New London, Connecticut, in May 1964.

10 Feb., 1964

After examining the Parachute Drift Table, Figure 6-3 in CG-308, it seemed that most of the tabular values were linearly related. I plotted these values as a family of curves of wind speed. I used the height of the parachute opening as the ordinate, and the actual drift as the abscissa. The curves didn't prove to be exactly linear but they were very nearly so. For some reason, I don't feel that this linearity should be so apparent. I decided to try to arrive at some purely analytical equation to describe the motion of the man as he comes down.

If we assume that he is jumping from a great height, we know that he has to free fall to at least 18,000 feet. At higher altitudes, he may suffer from anoxia, or stands the chance of freezing since the temperature is -5.3°F. In order to consider his motion in free fall, we must examine the components of his motion. They are due to:

1. The force of gravity.
2. The effect of the wind on him in a horizontal direction.
3. His motion due to the velocity of the airplane.

All of these components are opposed by the air resistance. The need for these equations is so we may have a very accurate entry for the computer.

The derivation follows.

Vertical Component of Free Fall

Let the y-axis be the vertical axis and be positive down.

Air Resistance, $R = c^2v^2$.

Definitions:

m = mass of the man

g = acceleration due to gravity (assumed constant)

$= 32.2 \text{ ft/sec}^2$

W = weight of the man $= mg$

$a_m = \frac{dv_m}{dt}$ = acceleration of the man

R = air resistance

c^2 = factor of proportionality

We may now start to write our equations.

$$m\frac{dv_m}{dt} = mg - c^2v_m^2$$

Let $k^2 = \frac{c^2}{m}$, then $\frac{1}{k^2}\cdot\frac{dv_m}{dt} = \frac{g}{k^2} - v_m^2$

Let $u^2 = g/k^2$

$$\frac{dv_m}{u^2-v_m^2} = k^2dt$$

$v_o = 0$ at time $t = 0$

$$\int_o^{v_m}\frac{dv_m}{u^2-v_m^2} = \int_o^t k^2dt$$

$$\frac{1}{u}\cdot\tanh^{-1}(v_m/u) = k^2t = \frac{g}{u^2}\cdot t$$

$$v_m = u\cdot\tanh\left(\frac{g}{u}\cdot t\right) \qquad (1)$$

As $t \rightarrow \infty$, $v_m = u$ as a limiting velocity.

We may write further equations of motion:

$$\frac{dy}{dt} = u \cdot \tanh\left(\frac{g}{u} \cdot t\right)$$

At $t = 0$, $y = 0$

$$\int_0^y \frac{dy}{dt} = \int_0^t u \cdot \tanh\left(\frac{g}{u} \cdot t\right)$$

$$y = \frac{u}{g/u} \ln \cosh\left(\frac{g}{u} \cdot t\right)$$

$$y = \frac{u^2}{g} \ln \cosh\left(\frac{g}{u} \cdot t\right)$$

Let $\lambda = \frac{g}{u}$

Then: $$y = \frac{u}{\lambda} \ln \cosh(\lambda t) \qquad (2)$$

$$\frac{\lambda y}{u} = \ln \cosh(\lambda t)$$

$$e^{\left(\frac{\lambda y}{u}\right)} = \cosh(\lambda t)$$

$$t = \frac{1}{\lambda} \cosh^{-1}\left[e^{\left(\frac{\lambda y}{u}\right)}\right] \qquad (3)$$

Refer to page 51, Betz, Burnham, Ewing. They say $u = 175 \frac{\text{ft.}}{\text{sec.}}$ for a man in free fall. From this we may evaluate an approximate value of c.

$$u = \sqrt{\frac{g}{k}} \qquad\qquad k = \frac{c}{\sqrt{m}}$$

$$u = \frac{\sqrt{gm}}{c} = \frac{\sqrt{W_m}}{c}$$

$$c = \frac{\sqrt{W_m}}{u} = \frac{\sqrt{180}}{175}$$

$$c = 0.0766 \qquad (A)$$

Horizontal Component of Motion Due to Wind

Assume: 1. Horizontal, steady wind

2. The average man is 6 feet tall and weighs 180 pounds. He presents a projected area, $A_m = 1125$ in.^{2}

Neglecting air resistance, we can write a few fundamental equations and find an equation for this motion.

F = force (pounds)

p = pressure (pounds per square inch)

A_m = projected area of the man (ft^2)

V_h = horizontal velocity of the man

V_w = velocity of the wind

$$F = pA_m = ma_h = m\frac{dV_h}{dt}$$

$$p = \frac{\gamma V_w^2}{zg} \quad \text{where velocity head} = \frac{V^2}{zg}$$

and density (pounds/ft^3) is equal to γ

$$m_m\frac{dV_h}{dt} = \frac{\gamma V_w^2 A_m}{zg}$$

But $m_m = \frac{W_m}{g}$

$$\frac{dV_m}{dt} = \frac{\gamma V_w^2 A_m}{zg\frac{W_m}{g}} = \frac{\gamma V_w^2 A_m}{zW_m}$$

Let $K^2 = \frac{\gamma V_w{}^2 A_m}{zW_m}$

Then: $K = V_w\sqrt{\frac{\gamma A_m}{zW_m}} = V_w\sqrt{\frac{0.08(1125)}{2(180)(144)}}$

$$K = (4.16 \times 10^{-2})V_w \qquad \text{(B)}$$

$$K^2 = 17.33 \times 10^{-4}V_w{}^2 \qquad \text{(C)}$$

$$\frac{dV_h}{dt} = K^2$$

$$V_h = K^2 t = 17.33 \times 10^{-4}V_w{}^2 t$$

For a wind velocity of 60 knots (101 ft/sec.):

$$V_h = (17.33 \times 10^{-4})(101)^2 t$$

$$V_h = 17.7t$$

For: $V < 15$ ft/sec., $R = cv$

15 ft/sec $< V <$ Sonic, $R = c^2v^2$

To get some idea of our proportionality, let us assume a free fall of 2000 feet; we must compute the time and thus, V_h.

$$y = 2000$$

$$c = 0.0766 \qquad c^2 = 58.8 \times 10^{-4}$$

$$m = \frac{W_m}{g} = \frac{180}{32.2} = 5.59$$

$$k^2 = c^2/m = 10.5 \times 10^{-4}$$

$$u^2 = g/k^2 = 3.06 \times 10^4$$

$$\lambda = g/u = 32.2/175 = 0.184$$

Substituting these values back into Equation (3) and solving:

$$t = 15.2 \text{ seconds}$$

and $V_h = 17.7t = 269$ ft/sec. $= 159.5$ knots

Therefore, we may assume that the resistance to his horizontal motion is proportional to the square of the velocity. Since he is in the same medium, the constant of proportionality should be the same since he should have the same limiting velocity if sufficient force were applied.

$$\frac{dV_h}{dt} = K^2 - c^2V_h^2$$

$$\frac{dV_h}{K^2 - c^2V_h^2} = dt$$

$$\frac{dV_h}{\frac{K^2}{c^2} - V_h^2} = c^2dt$$

Let $B^2 = K^2/c^2$

Then: $$\frac{dV_h}{B^2 - V_h^2} = c^2dt$$

At $t = 0$, $V_h = 0$

$$\int_0^{V_h} \frac{dV_h}{B^2 - V_h^2} = \int_0^t c^2dt$$

$$\frac{1}{B}\tanh^{-1}(V_h/B) = c^2t = \frac{K^2t}{B^2}$$

$$V_h = B\cdot\tanh(K^2t/B) \qquad (4)$$

As t increases, V_h approaches B as a limiting velocity.

$$B = \frac{K}{c} = \frac{4.16 \times 10^{-2}V_w}{7.66 \times 10^{-2}}$$

$$B = 0.543V_w$$

$$\int_0^x \frac{dx}{dt} = \int_0^t B\tanh(K^2t/B)$$

At $t = 0$, $x = 0$

$$x = \frac{B^2}{K^2} \ln \cosh(K^2 t/B)$$

But: $\frac{B^2}{K^2} = \frac{1}{c^2}$

$$x = \frac{1}{c^2} \ln \cosh(K^2 t/B) = \frac{1}{c^2} \ln \cosh\left(\frac{17.33 \times 10^{-4} V_W^2 t}{0.543 V_W}\right)$$

$$x = \frac{1}{c^2} \ln \cosh(3.19 \times 10^{-3} V_W t) \qquad (5)$$

CG-308 gives the values for parachute drift for a wind of given velocity, but this appears to be based on the assumption that his initial velocity is zero in both the vertical and horizontal planes. However, if we are to determine the initial navigational error of the aircraft at the instant the pilot leaves the plane, the pilot is traveling with a velocity equal to that of the plane.

To write an equation for this component of his motion, we will consider that there is no wind and the plane is flying horizontally at constant speed.

We will define the y-axis as the vertical and the x-axis as the horizontal in the direction of his motion.

Since we know that his initial velocity is that of the airplane, and there is no force acting on him except that of air resistance, he will decelerate to zero velocity. And since his initial velocity is so great, we can readily assume that the resistance is proportional to the square of the velocity.

Horizontal Motion Due to Initial Velocity

k^2 = constant or factor of proportionality

V_u = velocity due to that of the airplane

V_o = initial velocity

$$m\frac{dV_u}{dt} = -k^2 V_u{}^2$$

$$\int_{V_o}^{V_u} \frac{dV_u}{V_u{}^2} = \int_{o}^{t} \frac{-k^2 dt}{m}$$

$$-\frac{1}{V_u}\Bigg]_{V_o}^{V_u} = \frac{-k^2 t}{m}$$

$$\frac{1}{V_u} - \frac{1}{V_o} = \frac{k^2 t}{m}$$

$$1 - \frac{V_u}{V_o} = V_u\frac{k^2 t}{m}$$

$$1 = V_u\left(\frac{k^2 t}{m} + \frac{1}{V_o}\right)$$

$$1 = V_u\left(\frac{V_o k^2 t}{V_o m} + 1\right)$$

$$1 = V_u\left(\frac{V_o k^2 t + m}{m V_o}\right)$$

$$V_u = \frac{m V_o}{V_o k^2 t + m} \qquad (6)$$

$$\frac{dx}{dt} = m V_o\left(\frac{1}{V_o k^2 t + m}\right)$$

At $t = 0$, $x = 0$

$$\int_{o}^{x} dx = \int_{o}^{t} m V_o \frac{dt}{V_o k^2 t - m}$$

$$x = \frac{m}{k^2} \ln(V_o k^2 t + m) \Big]_o^t$$

$$x = \frac{m}{k^2}\Big[\ln(V_o k^2 t + m) - \ln(m)\Big]$$

$$x = \frac{m}{k^2} \ln\left(\frac{V_o k^2 t + m}{m}\right)$$

$$x = \frac{m}{k^2} \ln\left(\frac{V_o k^2 t}{m} + 1\right)$$

Let $b^2 = \frac{m}{k^2}$

$$x = b^2 \ln\left(\frac{V_o t}{b^2} - 1\right) \qquad (7)$$

Here I must state that a few other assumptions have been made. These are:

1. The rotation of the earth has been neglected.
2. The coriolis force has been neglected.
3. The sphereicity of the earth has been neglected.

I feel that these assumptions would not materially affect the accuracy of the drift. This is so because of the short distances involved.

Initially, the formulae were derived for conditions giving a limiting velocity of 175 ft/sec. This value was taken from Differential Equations with Engineering Applications, page 51. We know that air resistance or parasite drag has the form $D = C_d \frac{\rho}{2} A$ (Theory of Flight--von Mises--page 95). This corresponds to $c^2 = C_d \frac{\rho}{2} A$ in our initial

derivation. There we assumed that the value of c^2 was constant. A quick glance at this equation immediately reveals that c^2 is not constant since it depends on the air density which varies with altitude.

The area, A, is the projected or frontal area of the body under consideration. In order to get the maximum value of drift, I have assumed that the projected area of the man will be the effective area in all three cases of motion. Since a body will move with the frontal area normal to the direction of movement, we will use this in free fall, motion due to the wind, and motion due to initial velocity and thus have the maximum drift. This value will then be a constant.

The density of the air, ρ, depends on the barometric pressure and the temperature of the air. Since each of these vary with altitude, the density in turn varies with altitude. I will use the values of pressure and temperature for the U. S. Standard Atmosphere and plot these values against altitude. Hopefully, I will be able to write an equation defining this variation.

The third factor is the drag equation is C_d, the coefficient of drag. C_d depends on the shape of the body and the Reynolds number of the flow.

$\mathbb{R} = \frac{VL}{\nu}$ = Reynolds Number

V = velocity

L = length

$\nu = \frac{\mu}{\rho}$ = kinematic viscosity of the air

μ = dynamic viscosity of the air

ρ = density of the air

The dynamic viscosity, μ, varies with the temperature but not with pressure. (Applied Fluid Mechanics - page 338). Therefore we may plot μ against temperature and in turn convert it to altitude. With this and the plot of density, we may plot the kinematic viscosity, ν, versus altitude.

With this, we may investigate the variation in $\mathcal{R}$ and thus the variation in C_d.

Data for plot of Dynamic Viscosity versus Temperature. Ref: Table 52 - Handbook of Meteorology - Berry, Bollay, and Beers - McGraw Hill - New York - 1945.

Temperature °C	Temperature °F	Dynamic Viscosity gram/cm-sec. (x 10^{-6})	Dynamic Viscosity pound-sec./ft.^{2} (x 10^{-7})
-70	-94	172	3.595
-50	-58	147	3.075
-30	-22	152	3.180
-10	14	162	3.380
0	32	172	3.595
10	50	177	3.700
20	68	181	3.780
30	86	186	3.880
40	104	191	3.99

Data for plot of Barometric Pressure, Temperature, and Dynamic Viscosity versus Altitude. Ref: Pressure and Temperature - Handbook of Meteorology, Dynamic Viscosity - Plot of vs. Temperature.

Altitude Ft.x 1000	Barometric Pressure mm. of Hg	Temperature °F	Dynamic Viscosity pound-sec./ft.^{2} (x 10^{-7})
0	760.0	59.0	3.735
1	732.9	55.4	3.720
2	706.6	51.8	3.707
3	681.1	48.4	3.695
4	656.3	44.8	3.680
5	632.3	41.2	3.663
6	609.0	37.6	3.643
7	586.4	34.0	3.618
8	564.4	30.6	3.579
9	543.2	27.0	3.526
10	522.6	23.4	3.473
11	502.6	19.8	3.430
12	483.3	16.2	3.396
13	464.5	12.6	3.369
14	446.4	9.1	3.348
15	428.8	5.5	3.325
16	411.8	1.9	3.304
17	395.3	-1.7	3.286

Data continued:

18	379.4	-5.3	3.226
19	364.0	-8,7	3.248
20	349.1	-12.3	3.230
21	334.7	-15.9	3.212
22	320.8	-19.5	3.193
23	307.4	-23.1	3.174
24	294.4	-26.5	3.157
25	281.9	-30.1	3.140
26	269.8	-33.7	3.125
27	258.1	-37.3	3.111
28	246.9	-40.9	3.100
29	236.0	-44.5	3.090
30	225.6	-47.9	3.083
31	215.1	-53.5	3.0756
32	205.8	-55.1	3.0750
33	196.4	-58.7	3.076
34	187.4	-62.3	3.081
35	178.7	-65.7	3.093
36	170.4	-67.0	3.101
37	162.4	-67.0	3.101
38	154.9	-67.0	3.101
39	147.6	-67.0	3.101
40	140.7	-67.0	3.101
41	134.2	-67.0	3.101

Data continued:

42	127.9	-67.0	3.101
43	122.0	-67.0	3.101
44	116.3	-67.0	3.101
45	110.8	-67.0	3.101
46	105.7	-67.0	3.101
47	100.7	-67.0	3.101
48	96.05	-67.0	3.101
49	91.57	-67.0	3.101
50	87.30	-67.0	3.101

The density of the air and the kinematic viscosity may now be calculated.

$$\rho = \frac{p}{gRT}$$

where: p = pressure

g = acceleration due to gravity (assumed constant)

R = gas constant for Air

T = temperature

$$\nu = \frac{\mu}{\rho}$$

Altitude	Density = ρ	Kinematic Viscosity
Ft. x 1000	Slugs/ft^3 (x 10^{-3})	Ft^2/sec. x 10^{-4} ν
0	2.38	1.569
1	2.305	1.614
2	2.245	1.652
3	2.159	1.711
4	2.115	1.740

Data continued:

5	2.050	1.789
6	1.985	1.838
7	1.930	1.872
8	1.868	1.916
9	1.813	1.942
10	1.759	1.976
11	1.705	2.010
12	1.648	2.061
13	1.595	2.110
14	1.548	2.165
15	1.492	2.228
16	1.449	2.284
17	1.400	2.348
18	1.357	2.412
19	1.309	2.485
20	1.264	2.555
21	1.225	2.620
22	1.180	2.704
23	1.142	2.765
24	1.103	2.860
25	1.069	2.947
26	1.028	3.043
27	0.994	3.130
28	0.960	3.232

Data continued:

29	0.921	3.354
30	0.888	3.475
31	0.864	3.540
32	0.825	3.730
33	0.794	3.875
34	0.765	4.080
35	0.735	4.210
36	0.705	4.405
37	0.671	4.624
38	0.639	4.860
39	0.610	5.094
40	0.581	5.342
41	0.555	5.595
42	0.529	5.876
43	0.504	6.165
44	0.481	6.450
45	0.457	6.800
46	0.436	7.121
47	0.416	7.470
48	0.397	7.831
49	0.379	8.202
50	0.361	8.610

Now that we have the various graphs plotted, we have to investigate the variation in the Reynolds Number to deter-

mine the variation in the drag coefficient.

$$\mathbb{R} = \frac{VL}{\nu}$$

At 50,000 feet: $\nu = 8.61 \times 10^{-4}$

$\rho = 0.361 \times 10^{-3}$

$\mu = 3.101 \times 10^{-7}$

At 10,000 feet: $\nu = 1.976 \times 10^{-4}$

$\rho = 1.759 \times 10^{-3}$

$\mu = 3.473 \times 10^{-7}$

The weight of the man need be revised to account for the weight of the parachute and the flight suit. If we figure 20 pounds each for the last two items, $mg = W = 220$ pounds.

We must assume a shape for the man. There are two possibilities:

1. Circular cylinder, $d = 1.5$ feet
2. Ellipsoid, $L \doteq 6$ feet, $d \doteq 1.5$ feet

In both cases, the Reynolds Number will be the same.

At 50,000 feet: $\mathbb{R} = \frac{Vd}{\nu} = \frac{V(1.5)}{8.61 \times 10^{-4}} = 1.738 \times 10^{3} V$

At 10,000 feet: $\mathbb{R} = \frac{Vd}{\nu} = \frac{V(1.5)}{1.976 \times 10^{-4}} = 7.59 \times 10^{3} V$

When the man is wearing a flight suit with boots and helmet and has a parachute on, he will more closely approximate a circular cyclinder. For this reason, and the fact that there is very little data on ellipsoids, I will use the

form of a circular cylinder.

From Weisberger's experiments, if we can keep $\mathbb{R} > 5 \times 10^5$, we will have a constant value for C_d. (Applied Hydro-and-Aero-Mechanics, Prandtl and Tietjens).

We will examine $\mathbb{R}$ at both 50,000 and 10,000 feet to determine what velocity we must have.

At 50,000 feet: $\mathbb{R} = 5 \times 10^5 = 1.738 \times 10^3 V$

V must equal 288 ft./sec.

At 10,000 feet: $\mathbb{R} = 5 \times 10^5 = 7.59 \times 10^3 V$

V must equal 65.9 ft./sec.

To see if this is possible, we must check the limiting velocity at each altitude. We know that the limiting velocity is reached when the drag equals the weight since there is no acceleration.

With $\mathbb{R} = 5 \times 10^5$, $C_d = 0.33$ for an infinite cylinder (Handbook of Engineering Fundamentals - Eshbach).

$$D = W = C_d \frac{\rho}{2} V^2 A$$

At 50,000 feet: $V^2 = \frac{2W}{C_d \rho A} = \frac{2(220)(1.44)}{0.33(0.361 \times 10^{-3})(11.25)}$

$$V^2 = 47.3 \times 10^4$$

$$V = 685 \text{ ft./sec.}$$

We found that we must have a velocity of 288 ft./sec. so our assumption is valid at 50,000 feet.

At 10,000 feet: $V^2 = \frac{2W}{C_d \rho A} = \frac{2(220)(144)}{0.33(1.759 \times 10^{-3})(1125)}$

$$V^2 = 9.8 \times 10^4$$

$V = 314$ ft./sec.

We must have a velocity of 65.9 ft./sec., so our assumption is also valid at 10,000 feet.

This criterion of $\mathbb{R} > 5 \times 10^5$ will hold true every where between 10,000 and 50,000 feet. This becomes obvious when examining the curves.

With $\mathbb{R} > 5 \times 10^5$, we may enter Table III in Rouse, page 249, and find that for a length-diameter ratio of 5 (which is very nearly what we have), $C_d = 0.35$.

Looking toward the same problem with a parachute, this investigation has also revealed a value of $C_d = 1.33$ for a parachute. (Theory of Flight - von Mises - page 98). This value is in agreement with the values found in other texts for a hemisphere, hollow upstream. The criterion here is that $\mathbb{R} > 10^3$ which is easily recognized.

It should be noted that these values of critical Reynolds Numbers decrease with increasing turbulence of the air. The values used herein are for air with no turbulence in the approaching stream. (Fluid Mechanics - Cox and Germano - p.242). This gives us a factor of safety since the air will be turbulent.

We have now covered the factors with one exception, density. Therefore, the problem at hand is writing an equation which describes the density variation.

From the plot of density versus altitude, it appears

that we have a decreasing exponential. This will give us an equation in the form of

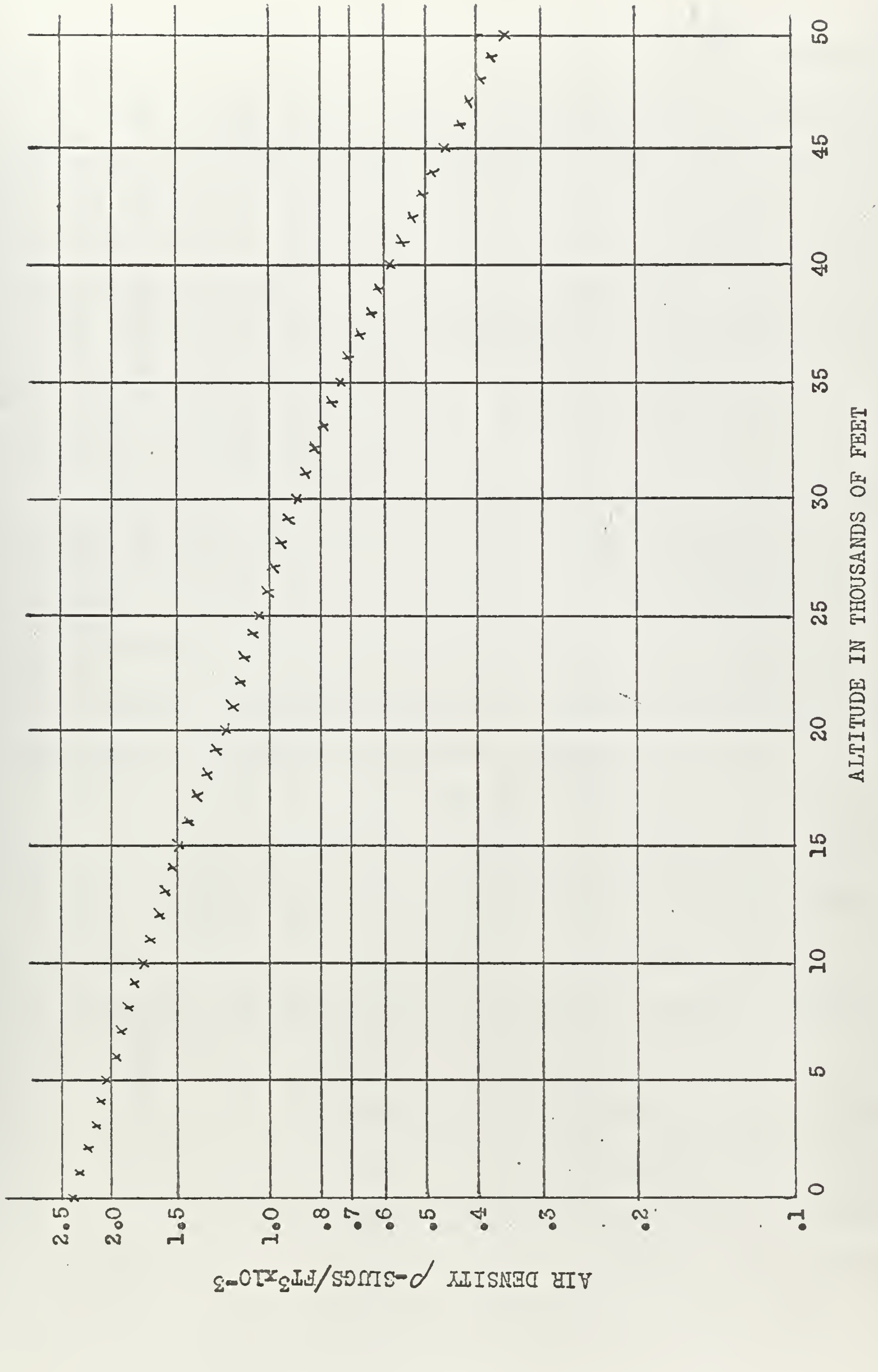
$$\rho = Ae^{-By}$$

A plot of ρ vs. altitude on semi-log paper will give us an indication of whether or not we have an exponential relationship. (See graph next page).

By sighting down the plot, it is seen that we do not have a straight line. However, a straight line fits the curve from 0 to 32,000 feet, and another from 32,000 to 50,000 feet.

I would rather approximate the relationship with one smooth curve rather than make it discontinuous. The problem we now have is that of tolerances. How much tolerance can we allow and where should errors be a minimum?

With this determined we only have to integrate and the man's motion is defined.


AIR DENSITY ρ-SLUGS/FT³x10⁻³
2.5
2.0
1.5
1.0
.8
.7
.6
.5
.4
.3
.2
.1
ALTITUDE IN THOUSANDS OF FEET
0
5
10
15
20
25
30
35
40
45
50

RLA

11 March 1964

From the plot of vs. y on semi-log paper, we may approximate the curve with a straight line. The equation has the form

Let $= 2.40 \times 10^{-3}$

For our first approximation, consider

$y = 35{,}000$ feet, where $= 0.735 \times 10^{-3}$

From this, $B = -3.375 \times 10^{-5}$

With this as a starting point, we may find the differences between the formula value and the actual value. The value of B may then be adjusted to give differences which are acceptable.

Several adjustments give $B = -3.44 \times 10^{-5}$. For this value, the following differences exist.

$$B = -3.44 \times 10^{-5}$$

(Values for Actual density, formula density and the difference between formula density and actual density are all expressed as slugs/ft.^{3} x 10^{-3}. Altitude is in thousands of feet).

Altitude	Actual Density	Formula Density	Difference
0	2.38	2.40	0.02
5	2.050	2.021	-0.029
10	1.759	1.700	-0.059
15	1.492	1.433	-0.059
20	1.264	1.209	-0.055

Data continued:

25	1.069	1.040	-0.029
30	0.888	0.856	-0.032
35	0.735	0.731	-0.004
40	0.581	0.607	0.026
45	0.457	0.510	0.053
50	0.361	0.430	0.069

We now have an equation for the density of air as a function of altitude.

$$\rho = 2.40 \times 10^{-3} e^{(-3.44 \times 10^{-5} y)}$$

Now we can proceed and integrate our basic equation for free fall. At this time, I will use the letter h to designate altitude and y will be used strictly for vertical displacement. Therefore, $y = h_o - h$ where h_o is the altitude at which the fall began. The relationship for air density now becomes

$$\rho = 2.40 \times 10^{-3} e^{(-3.44 \times 10^{-5} h)}$$

Our primary equation is now

$$\Rightarrow \frac{m\,dV}{dt} = mg - C_d \frac{\rho_c}{2} e^{Bh} V^2 A_m$$

Let $C_d \frac{\rho_c}{2} A_m = C$. Then $\frac{m\,dV_m}{dt} = mg - CV_m^2 e^{Bh}$

Since $y = h_o - h$, $h = h_o - y$ where $y = \int V dt$

$$\frac{m\,dV_m}{dt} = mg - CV_m^2 \frac{e^{Bho}}{e^{By}}$$

For a given altitude, e^{Bho} is constant.

Let $Ce^{Bho} = D$

Since B is negative, we have

$$m\frac{dV_m}{dt} = mg - DV_m^2e^{By}$$

I have tried for over a week to integrate this equation consulting every differential equation textbook that I could find. This has not produced any positive results. Since this equation appears to be impossible to integrate, we can also approximate the relationship for density as a series of straight lines of changing slope. We may consider each curve over a definite interval and take three intervals in order to make a good approximation. This equation has the form

$$\rho = ah + b$$

The first interval we shall consider is

(1) $0 \leq h \leq 14{,}000$ feet

At $h = 0$, $\rho = 2.37 \times 10^{-3}$

$\Rightarrow b_1 = 2.37 \times 10^{-3}$

At $h = 14{,}000$, $\rho = 1.53 \times 10^{-3}$

$\Rightarrow a_1 = -6.00 \times 10^{-8}$

Therefore, $\rho_1 = -6.00 \times 10^{-8}h + 2.37 \times 10^{-3}$

The second interval is

(2) $14{,}000 \leq h \leq 30{,}000$ feet

At $h = 14{,}000$, $\rho = 1.53 \times 10^{-3}$

$\Rightarrow b_2 = 1.53 \times 10^{-3}$

At $h = 30{,}000$, $\rho = 0.87 \times 10^{-3}$

$\Rightarrow a_2 = -4.125 \times 10^{-8}$

Therefore, $\rho_2 = -4.125 \times 10^{-8}h + 1.53 \times 10^{-3}$

The third interval is

(3) $30{,}000 \leq h \leq 50{,}000$ feet

At $h = 30{,}000$, $\rho = 0.87 \times 10^{-3}$

$\Rightarrow b_3 = 0.87 \times 10^{-3}$

At $h = 50{,}000$, $\rho = 0.34 \times 10^{-3}$

$\Rightarrow a_3 = -2.65 \times 10^{-8}$

Therefore, $\rho_3 = -2.65 \times 10^{-8}h + 0.87 \times 10^{-3}$

With our density described in another form, we may again write the differential equation for the man's motion. Now we have

$$\frac{mdV_m}{dt} = mg - C_d\frac{(ah + b)}{2}V_m^2A_m$$

$$\frac{mdV_m}{dt} = mg - C_d\frac{aA_m}{2}hV_m^2 - C_d\frac{bA_m}{2}V_m^2$$

Let $\frac{C_dA_m}{2} = C_a$, then $\frac{mdV_m}{dt} = mg - C_aahV_m^2 - C_abV_m^2$

But again, $y = \int Vdt = h_o - h$, and $h = h_o - y$

$$\frac{mdV_m}{dt} = mg - C_aa(h_o - y)V_m^2 - C_abV_m^2$$

$$\frac{mdV_m}{dt} = mg - (C_aah_o + C_ab)V_m^2 + C_aayV_m^2$$

Again, I have worked several days on this equation and have been unable to integrate it.

If we can't integrate this equation, or the one

involving the exponential relationship for density, then we must find some way of approximating this solution.

Assume for the present that we have a constant density. In that case, our original integration holds and we have

(1) $V_m = u\tanh(gt/u)$

(2) $y = (u/\lambda)\ln\cosh(\lambda t)$

(3) $t = \frac{1}{\lambda}\cosh^{-1}\left(e^{\lambda y/u}\right)$

$$u^2 = \frac{g}{k^2};\quad k^2 = \frac{c^2}{m};\quad c^2 = C_d\frac{\rho}{2}A_m;\quad \lambda = \frac{g}{u};\quad \lambda^2 = \frac{g^2}{u^2};$$

$$\frac{\lambda^2}{u^2} = \frac{g^2}{g^2/k^4} = k^4 \quad\text{and}\quad \frac{\lambda}{u} = k^2 = \frac{c^2}{m}$$

$$\frac{1}{\lambda} = \frac{u}{g} = \frac{\sqrt{g}}{gk} = \frac{\sqrt{m}}{c\sqrt{g}} = \frac{1}{g}\sqrt{\frac{2W}{C_d\rho A_m}}$$

$$\frac{u}{\lambda} = \frac{2W}{gC_d\rho A_m} \quad\text{and}\quad \lambda = g\sqrt{\frac{C_d\rho A_m}{2W}}$$

Therefore, $u = \sqrt{\frac{2W}{C_d\rho A_m}}$

$$\frac{g}{u} = g\sqrt{\frac{C_d\rho A_m}{2W}}$$

$$\frac{\lambda}{u} = \frac{gC_d\rho A_m}{2W}$$

In order for us to test the validity of this approximation, we must determine the numerical values and express these constants as functions of the density.

$$u = \sqrt{\frac{2W}{C_d\rho A_m}} = 12.7/\sqrt{\rho}$$

$$\frac{g}{u} = \frac{g}{12.7/\sqrt{\rho}} = 2.535\sqrt{\rho}$$

$$\frac{u}{\lambda} = \frac{2W}{gC_d\rho A_m} = \frac{5.02}{\rho}$$

$$\frac{1}{\lambda} = \frac{1}{g}\sqrt{\frac{2W}{C_d\rho A_m}} = \frac{0.394}{\sqrt{\rho}}$$

$$\frac{\lambda}{u} = \frac{gC_d\rho A_m}{2W} = 0.199\rho$$

We may now rewrite our equations as

$$(1) \quad V_m = \frac{12.7}{\sqrt{\rho}}\tanh(2.535\sqrt{\rho}\,t)$$

$$(2) \quad y = \frac{5.02}{\sqrt{\rho}}\ln\cosh(2.535\sqrt{\rho}\,t)$$

$$(3) \quad t = \frac{0.394}{\sqrt{\rho}}\cosh^{-1}\left[e^{(0.199\rho y)}\right]$$

If we analyze this method of solution over a large vertical displacement, we find that effectively, we are considering the density to be constant in accordance with our initial assumption. This will provide very inaccurate results. Therefore, if we are to assume constant density, we must limit our value of y to a small increment. I will arbitrarily choose a value of 1,000 feet for y as the interval of displacement. This I feel is a safe assumption and should not introduce any significant error. If we are to proceed in this manner, we must account for the initial velocity at the beginning of each of the intervals. To do this we must return to our original derivation where

$$\frac{m\,dV_m}{dt} = mg - c^2V_m^2$$

At $t = t$, $V_m = V_m$

At $t = 0$, $V_m = V_o$

If we integrate,

$$\tanh^{-1}(V_m/u)\Big]_{V_o}^{V_m} = (g/u)t$$

$$\tanh^{-1}(V_m/u) = (g/u)t + \tanh^{-1}(V_o/u) \quad \text{and}$$

$$V_m = u\tanh\left[(g/u)t + \tanh^{-1}(V_o/u)\right]$$

Integrating again

$$y = (u^2/g)\ln\cosh\left[(g/u)t + \tanh^{-1}(V_o/u)\right]$$

$$t = \frac{1}{\lambda}\left[\cosh^{-1}\left(e^{\lambda y/u}\right) - \tanh^{-1}(V_o/u)\right]$$

$$t = \frac{0.394}{\sqrt{\rho}}\left[\cosh^{-1}\left(e^{0.199\rho y}\right) - \tanh^{-1}\left(\frac{V_o\sqrt{\rho}}{12.7}\right)\right]$$

To pursue this method of solution, we must use the following method of approach, and we may use the exact values of air density. We will consider $h_o = 20{,}000$ feet. For $y = 1{,}000$ feet, we will determine the time for free fall to 19,000 feet assuming a constant air density equal to the value for 19,000 feet. We will also determine the velocity at 19,000 feet which will be the initial velocity which we shall use for the interval between 19,000 and 18,000 feet. Results of these calculations follow.

h	$\rho \times 10^{-3}$	V_m	V_o	t
19,000	1.309	223	0	8.16
18,000	1.357	224	223	4.48
17,000	1.400	222	224	4.50
16,000	1.449	221.5	222	4.51

In this case, t does not give the time of free fall except for the first 1,000 feet. It appears that here the man has reached the limiting velocity. Since the velocity changes very little, we may divide the average velocity for the interval into 1,000 feet to find the time of fall for that interval.

If we started the same procedure at say $h_o = 25{,}000$ feet, and at 17,000 feet had a velocity of 222 ft./sec., we could be reasonably sure that our approximation is correct. Let $h_o = 25{,}000$ feet.

h	$\rho \times 10^{-3}$	V_m	V_o	t
24,000	1.103	227	0	8.14
23,000	1.142	228	227	4.39
22,000	1.180	226.5	228	4.41

The tendency of these calculations is to verify each other. Our first thought would then be that this approximation is correct. But, let us look at the limiting velocities at the different altitudes.

$h = 17{,}000$ feet

$$V^2 = \frac{2W}{C_d \rho A_m}$$

$$V = 339 \text{ ft./sec.}$$

$h = 24{,}000$ feet, $V = 382$ ft./sec.

By our equation in the approximation, consider the interval of fall from 50,000 to 49,000 feet.

$49{,}000 \leq h \leq 50{,}000;\quad V = 245$ ft./sec.

$48{,}000 \leq h \leq 49{,}000;\quad V = 228$ ft./sec.

The limiting velocity at 48,000 feet is:

$V = 636$ ft./sec.

In all three cases, we notice quite a disparity between the velocity as determined by our equations and the limiting velocity. From this, I think we must accept the approximations as being invalid.

In order to determine the time of free fall, another method of approximation could be used. We could assume that the man has reached his limiting velocity and plot these values of limiting velocity versus altitude. By taking the average velocity over a 1,000 foot interval, we could find the time taken to traverse that interval. Now, suppose that this would give us results without appreciable error. We would then have no means to determine his horizontal motion because we have no knowledge of whether or not he will reach his limiting velocity in the horizontal direction.

For an accurate solution then, we must integrate our equations of motion. I will now write these equations and define all of the terms in summary form.

Our first set of equations, (1), (2), and (3), are for the condition of free fall. Bear in mind that the equation for the density of air may be either the exponential relationship or the linear relationship.

(1) Motion vertically downward.

$$\frac{m\,dV_m}{dt} = mg - \frac{C_d}{2}\left\{\begin{matrix}\rho_o e^{Bh}\\ \text{or}\\ ah + b\end{matrix}\right\}V_m^2 A_m$$

(2) Horizontal motion due to wind.

$$\frac{m\,dV_h}{dt} = \frac{\gamma V_w^2 A_m}{2g} - \frac{C_d}{2}\left\{\begin{matrix}\rho_o e^{Bh}\\ \text{or}\\ ah + b\end{matrix}\right\}V_h^2 A_m$$

(3) Horizontal motion due to initial velocity.

$$\frac{m\,dV_u}{dt} = -\frac{C_d}{2}\left\{\begin{matrix}\rho_o e^{Bh}\\ \text{or}\\ ah + b\end{matrix}\right\}V_u^2 A_m$$

It is easily seen that the results of equation (1) relating the displacement in free fall must be an input into equations (2) and (3) in the relationship for density.

The various terms are defined below.

m = mass of the man = $\frac{W}{g}$ in slugs

W = weight of the man in pounds

g = acceleration due to gravity = 32.2 ft./sec.^{2}

V_m = velocity of the man in the vertical direction in ft./sec.

V_h = velocity of the man in the horizontal direction due to the wind in ft./sec.

V_u = velocity of the man in the horizontal direction due to the initial velocity of the aircraft in ft./sec.

C_d = coefficient of drag = 0.35

A_m = projected area of the man = 1125 square inches

V_w = velocity of the wind in ft./sec.

γ = weight density of the air $= \rho g = g\left\{\begin{matrix}\rho_o e^{Bh} \\ \text{or} \\ ah + b\end{matrix}\right\}$

$\rho_o = 2.40 \times 10^{-3}$ slugs/ft.^{3}

$B = -3.44 \times 10^{-5}$ ft.$^{-1}$

h = altitude in feet

h_o = altitude of bail-out

y = vertical displacement in feet

$h = h_o - y$

a and b are defined for the following intervals:

$0 \leq h \leq 14{,}000$ $\quad a = -6.00 \times 10^{-8}$, $b = 2.37 \times 10^{-3}$

$14{,}000 \leq h \leq 30{,}000$ $\quad a = -4.125 \times 10^{-8}$, $b = 1.53 \times 10^{-3}$

$30{,}000 \leq h \leq 50{,}000$ $\quad a = -2.65 \times 10^{-8}$, $b = 0.87 \times 10^{-3}$

We must now look at the equations for fall with a parachute. Basically, there is no difference except for the values of C_d and the projected area.

For motion in the vertical direction, we may use a value of $C_d = 1.33$ (Theory of Flight - von Mises - page 98) for a parachute. This value is in agreement with those found in other textbooks for a hemisphere, hollow upstream, for a Reynolds number greater than 10^3. Hereafter, I will refer to this drag coefficient with the symbol C_{dy}.

Since we have assumed the shape of a hemisphere, the

projected area for motion in the vertical direction will be the area of a circle of a radius equal to fourteen feet. Therefore, $A_y = \pi(14)^2 = 615.4 \text{ ft}^2$.

For motion in the horizontal direction, the projected area, $A_h = \frac{1}{2}\pi(14)^2 = 307.7 \text{ ft.}^2$ This is the area of a semicircle of a radius of fourteen feet.

The determination of the drag coefficient for sidewise motion presents a problem since there have been no experiments performed for a hemisphere with its major axis perpendicular to the direction of flow. In the vertical direction, $C_{dy} = 1.33$ with the hollow end upstream. For a hemisphere with its hollow end downstream, $C_d = 0.34$. After checking in many fluid mechanics textbooks and studying the various drag coefficients for different bodies under several conditions of flow, and studying theoretical flow patterns and pictures of actual flow patterns, I will assume a drag coefficient for the parachute in the horizontal direction. The value which I have chosen is $C_{dh} = 0.80$.

Now, we may write our equations of motion for parachute fall.

(4) Vertical motion.

$$\frac{m\,dV_m}{dt} = mg - \frac{C_{dy}}{2}\left\{\begin{matrix}\rho_o e^{Bh} \\ \text{or} \\ ah + b\end{matrix}\right\} V_m^2 A_y$$

(5) Horizontal motion due to wind.

$$\frac{m\,dV_h}{dt} = \frac{\gamma V_w^2 A_h}{2g} - \frac{C_{dh}}{2}\left\{\begin{matrix}\rho_o e^{Bh} \\ \text{or} \\ ah + b\end{matrix}\right\} V_h^2 A_h$$

(6) Horizontal motion due to initial velocity.

$$m\frac{dV_u}{dt} = -\frac{C_{dh}}{2}\left\{\begin{matrix}\rho_o e^{Bh} \\ \text{or} \\ ah + b\end{matrix}\right\}V_u^2 A_h$$

$C_{dy} = 1.33$

$A_y = 615.4\ \text{ft}^2$

$C_{dh} = 0.80$

$A_h = 307.7\ \text{ft}^2$

The rest of the terms are the same as defined for equations (1), (2), and (3).

In all of the above equations, all must be integrated twice in order to give a displacement in the particular direction. Equations (1) and (4) must be solved for t by first integrating to find the displacement as a function of time and then transposing to find time as a function of displacement. If we call the time of free fall given by equation (1) t_1, then t_1 substituted into equations (2) and (3) gives the displacements in the horizontal direction. In the integration of equations (5) and (6), consideration must be given to the fact that there is an initial velocity. This initial velocity is the value given by the first integration (for V) of equations (2) and (3) at time t_1.

By summing up all of the horizontal values considering the direction as well as the magnitude given by our equations, over the period of time from t_o to t_1 (free fall) and from t_1 to t_4 (parachute fall), we have the parachute drift.

I would now like to write this problem in the form of a program flow chart. When the six equations of motion are integrated, these may be written as additional sub-routines and added to this program with a predefined connector. I will also omit all machine instructions since all processes are mathematical operations.

A few new terms were added in the flow chart which should be defined.

α = the direction in degrees toward which the wind is blowing.

β = the course of the aircraft when the man bails out.

θ = the resultant direction of parachute drift.

After all of this work, I feel that I should explain why I have put this much time in what is seemingly a minor matter. In a recent study of the feasibility of the use of a personnel locator beacon, the following facts were brought to light in a study of Naval aircraft accidents. The study showed that over 98% of all incidents occurred within 60 miles of a rescue facility. This is within the range of a good DF fix. Assuming that we know the location of the aircraft when the person leaves his craft, we should be able to find him as quickly as possible. By accounting for the variables discussed in the analysis of the problem, we may determine where he will be in the water with reasonable accuracy. In cases where the sea and air temperature are

critical, or where the man is injured, it is absolutely necessary that we rescue him as quickly as possible. It is apparent that this same solution is applicable over land areas.

This analysis of his motion in the air will make this possible upon the integration of his six equations of motion.

Chart ID AA Chart Name: Free Fall

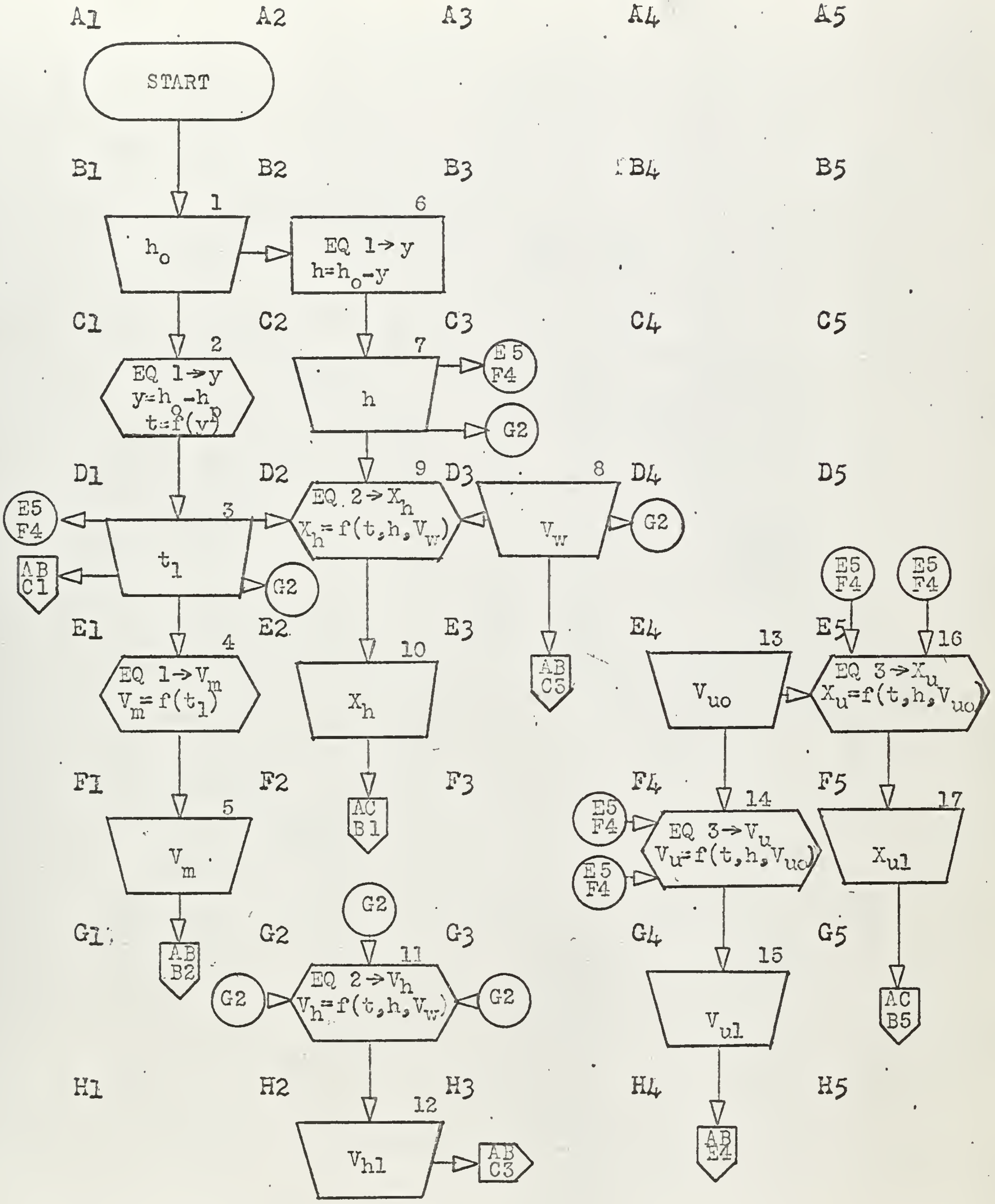


Chart ID AB Chart Name: Parachute fall

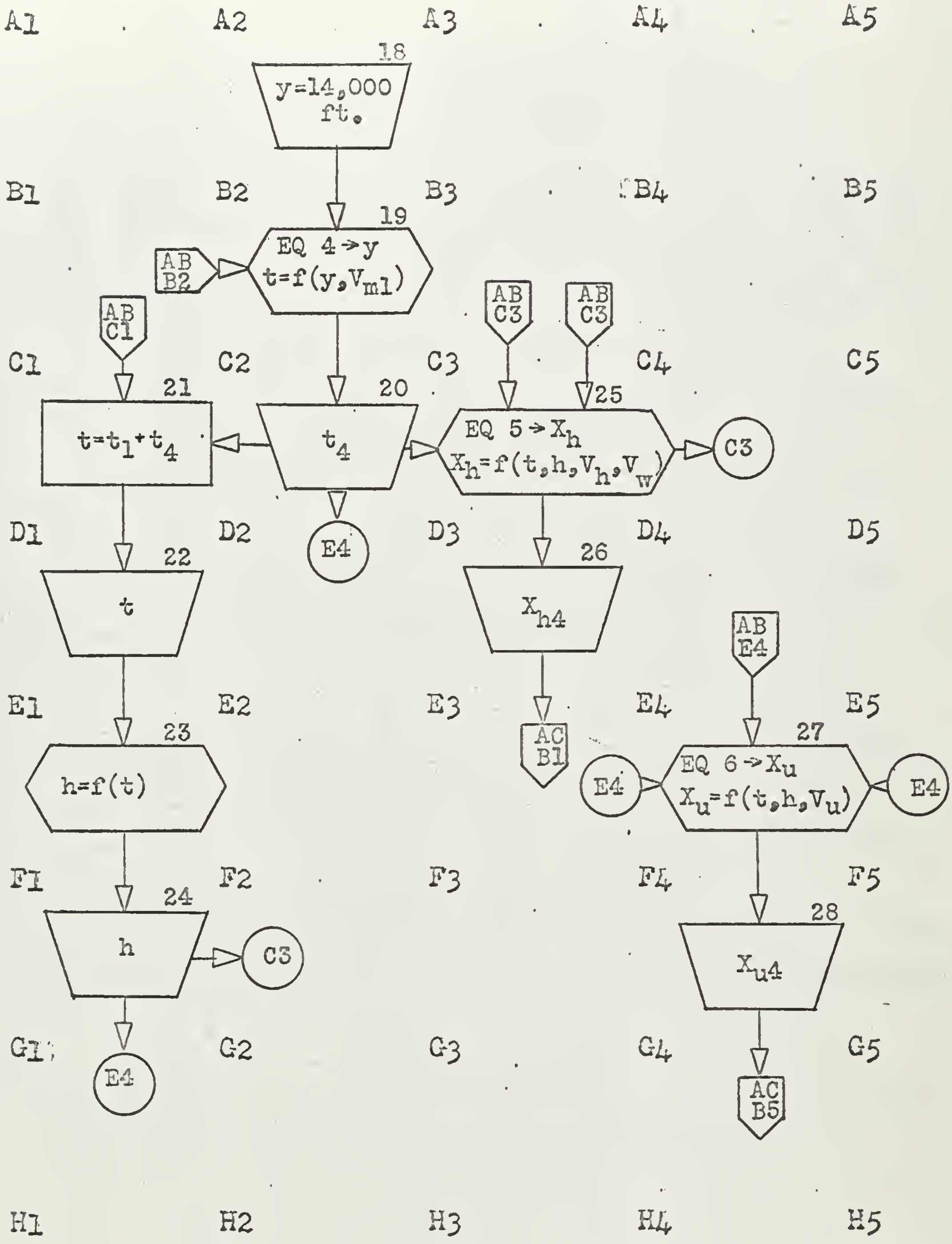


Chart ID AC Chart name: Parachute drift-direction

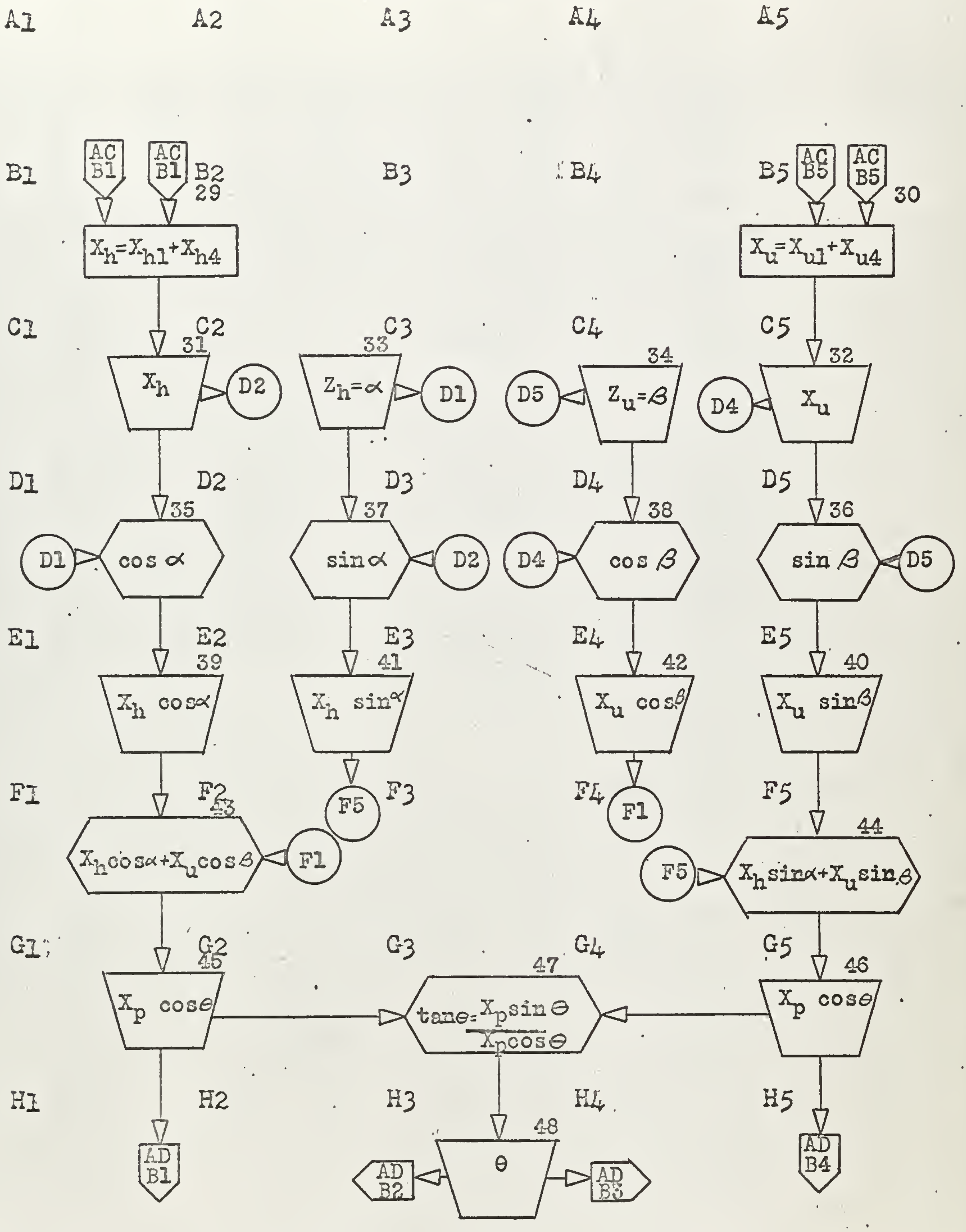
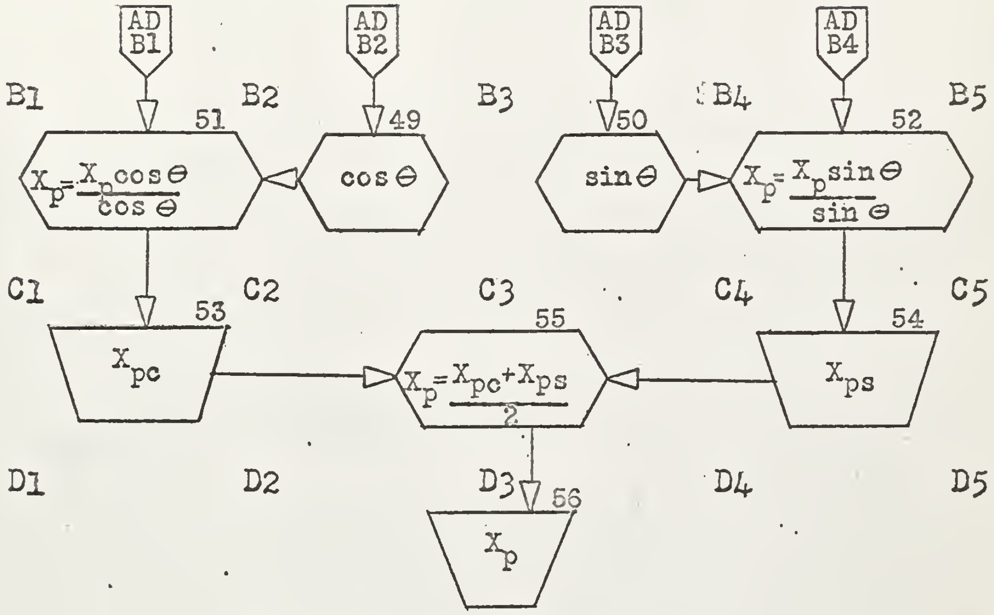


Chart ID AD Chart name: Parachute drift-magnitude

A1 A2 A3 A4 A5


AD B1
AD B2
AD B3
AD B4
B1
B2
B3
B4
B5
51
49
50
52
$X_p = \frac{X_p \cos\theta}{\cos\theta}$
$\cos\theta$
$\sin\theta$
$X_p = \frac{X_p \sin\theta}{\sin\theta}$
C1
C2
C3
C4
C5
53
55
54
X_{pc}
$X_p = \frac{X_{pc} + X_{ps}}{2}$
X_{ps}
D1
D2
D3
D4
D5
56
X_p

E1 E2 E3 E4 E5

F1 F2 F3 F4 F5

G1 G2 G3 G4 G5

H1 H2 H3 H4 H5

APPENDIX D.

EXTRACTS FROM THE STUDY:

"FREE FALL AND PARACHUTE DRIFT"

APPENDIX D.

EXTRACTS FROM THE STUDY:

"FREE FALL AND PARACHUTE DRIFT"

"Free Fall and Parachute Drift" was an undergraduate study performed by Cadet First Class Darvy M. Cohan at the U. S. Coast Guard Academy, New London, Connecticut, in the spring of 1965. Cohan expanded and refined the work done by Armacost and Saunders which appears in the preceding Appendix. Cohan expanded the problem to include the effect of winds at three different altitudes blowing with different forces and in different directions. He also considered the possibilities of the parachute opening at three different altitudes: (1) the altitude at which the aircraft was flying, (2) automatically at 14,000 feet, and (3) at the surface of the Earth (parachute fails to open).

Cohan developed three computer programs, one mainline program and two subroutines, all of which are included in this Appendix. A brief description of each program precedes the program itself. The flow diagrams are taken directly from the original paper.

VECTOR SUM PROGRAM

Cohan's entire program hinged upon the development of a program

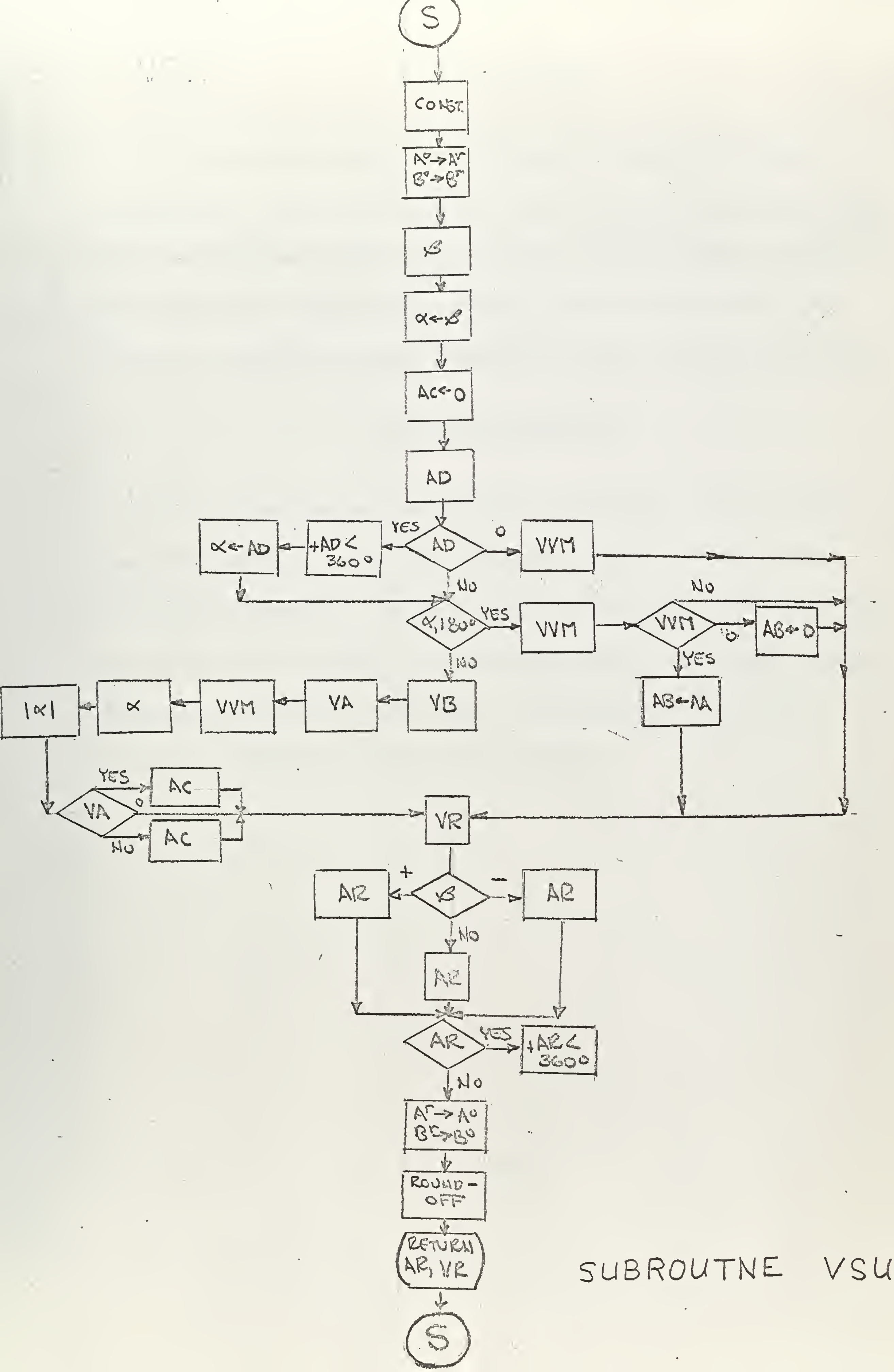
to sum vectors in three dimensions. The path of motion represented a resultant vector which made an angle θ with the horizontal. Using sine and cosine functions of that angle he determined the vertical and horizontal distances a man would travel in a specified time interval, given the velocity component, V, within the air mass. The total horizontal displacement relative to the air mass is the sum of the distances for all time intervals and is represented by DTR. By applying the horizontal motion of the air mass the final resultant motion with respect to the Earth's surface is obtained.

The theory behind his vector sum program, VSUM, was this:

1. Establish one vector as the major axis used by the computer.

2. Build a triangle using the angle between two vectors. One leg would then be the first vector plus the projection of the second onto the major axis. The other leg would be the projection of the second vector upon the orthogonal axis. Dividing the first leg into the second leg produces the tangent of the angle of the resultant vector.

3. Design a dummy system to work with the azimuth angles found in the real world. Convert the azimuth angles to the dummy system, solve the problem, and convert back to azimuth angles.



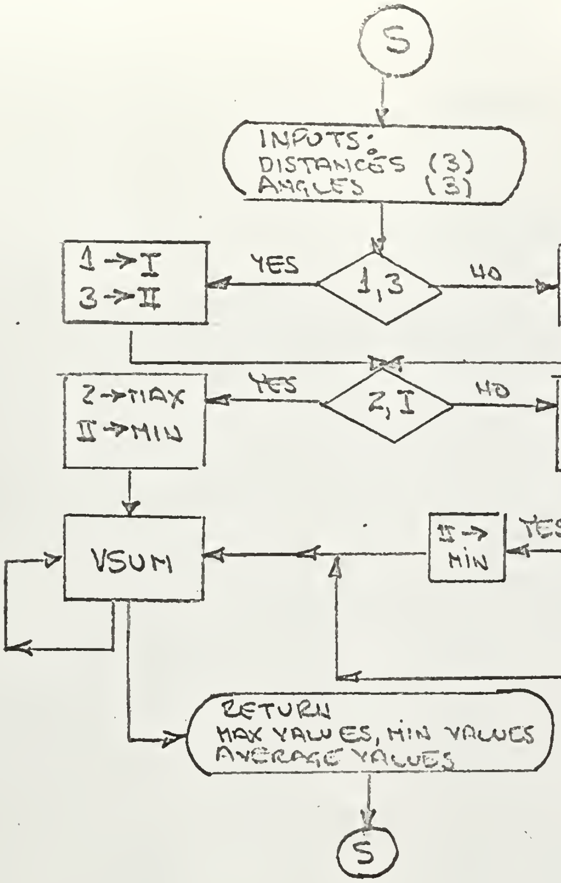
SUBROUTNE VSUM

SUBROUTINE ORDER

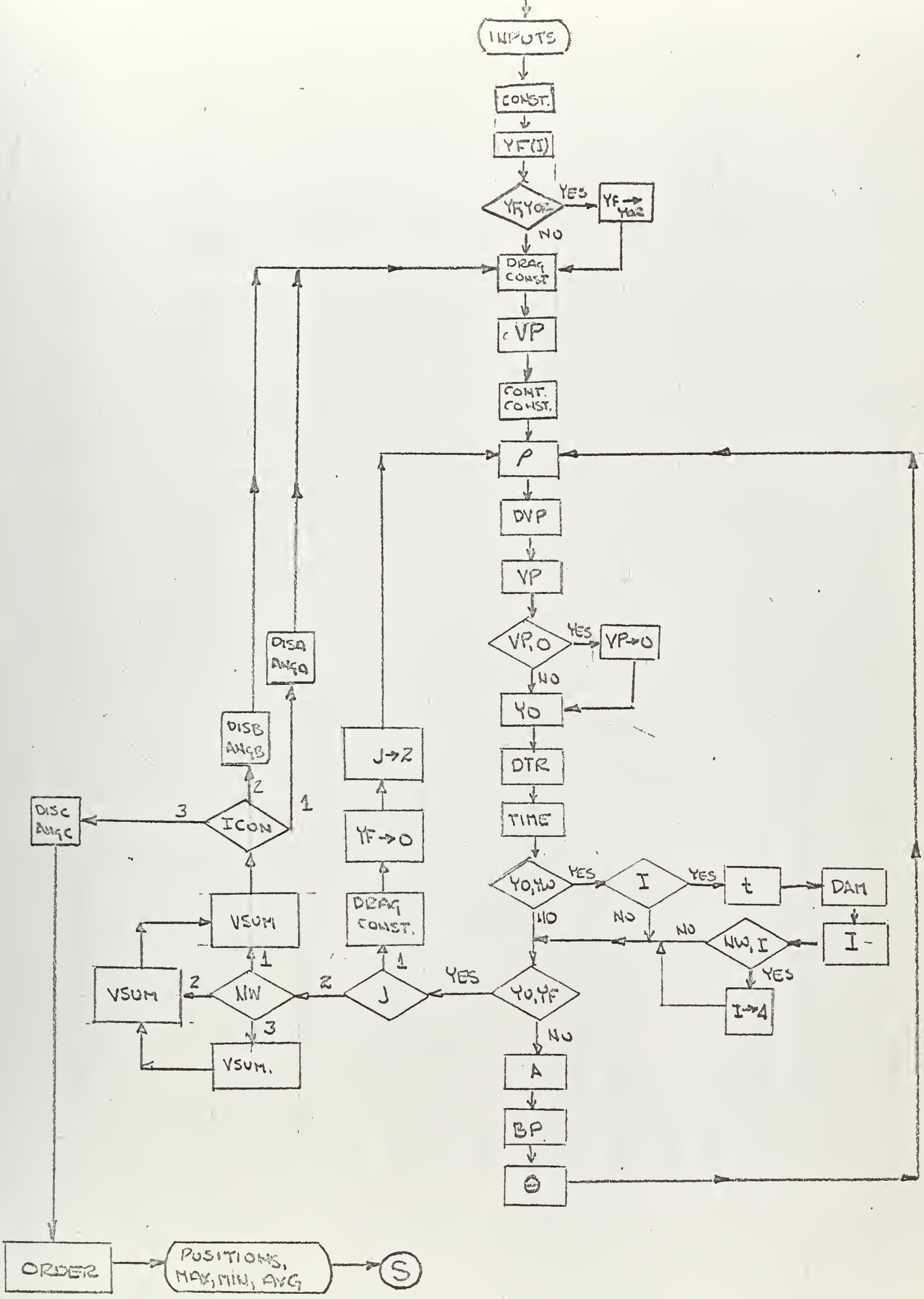
In considering the three possible parachute-opening altitudes, Cohan ended up with three possible vectors at the Earth's surface, DISA, DISB, and DISC with their associated angles, ANGA, ANGB, and ANGC. His SUBROUTINE ORDER takes the three vectors, arranges them from maximum to minimum and then produces the vector average of the three.

MAINLINE PROGRAM

The mainline program, called SUBROUTINE PARAD, uses the two preceding subroutines and the basic equations found in the study by Armacost and Saunders. The Euler method of statistical integration was applied for time intervals of two seconds in the free fall phase and four seconds in the parachute drift phase. The exponential form of the equations involving air density were employed.



SUBROUTINE ORDER



FREE FALL AND PARACHUTE DRIFT

```
C  C  FREE FALL AND PARACHUTE DRIFT
      DIMENSION WV(3),AVW(3),YW(3),DAM(3),YF(3)
  100 FORMAT(2F12.2)
  104 FORMAT(F4.0,F6.0,F6.0)
  105 FORMAT(I5)
  106 FORMAT(F5.0,F4.0,F6.0)
  107 FORMAT(34HENTER WIND DATA, PRESS START      )
      READ 104,AVM,VM,YOR
      PRINT 107
      PAUSE
      READ 105,NW
      READ 106,(WV(I),AVW(I),YW(I),I=1,NW,1)
      CALL VSUM(AVM,AVW(1),VM,WV(1),VR,AVR)
      W=220.
      B=0.0000344
```

```
      E=2.7183
      ICON=0
      YF(2)=14000.
      YF(3)=0
      IF(YOR-14000.)11,11,12
   11 YF(2)=YOR
   12 YF(1)=YOR
   13 YO=YOR
      H=2.
      C=2.73
      T=0
      DTR=0
      J=1
      I=1
      TIME=0
      THETA=0
      VP=VR
      ICON=ICON+1
```

```
1   X=B*YO
    P=0.0012/EXP(X)
    DVP=(W*SIN(THETA)-C*P*VP**2)*.1464
    VP=VP+DVP*H
    IF(VP)2,2,3
2   VP=0
3   YO=YO-VP*SIN(THETA)*H
    DTR=DTR+VP*COS(THETA)*H
    TIME=TIME+H
    IF(YO-YW(I))70,70,35
35  IF(YO-YF(ICON))5,5,4
4   A=VP+32.2*SIN(THETA)*H
    BP=32.2*COS(THETA)*H
    THETA=THETA+ATAN(BP/A)
    GO TO 1
5   GO TO (6,74),J
6   C=827.2
    YF(ICON)=0
```

```
      J=2
      H=4.
      GO TO 1
   70 GO TO (71,71,71,35),I
   71 T=TIME-T
      DAM(I)=T*WV(I)
      I=I+1
      IF(NW-I)72,35,35
   72 I=4
   73 GO TO 35
   74 GO TO (77,76,75),NW
   75 CALL VSUM (AVW(3),AVW(2),DAM(3),DAM(2),DAM(2),AVW(2))
   76 CALL VSUM (AVW(2),AVW(1),DAM(2),DAM(1),DAM(1),AVW(1))
   77 CALL VSUM (AVR,AVW(1),DTR,DAM(1),DT,ADT)
      GO TO (80,81,82),ICON
   80 DISA=DT*.00016458
      ANGA=ADT
      GO TO 13
```

```
81 DISB=DT*.00016458
   ANGB=ADT
   GO TO 13
82 DISC=DT*.00016458
   ANGC=ADT
   CALL ORDER(DISA,ANGA,DISB,ANGB,DISC,ANGC,DMAX,AMAX,DMIN,AMIN,DAVG,
  1AAVG)
   CONTINUE
   PRINT 100,AMAX,DMAX
   PRINT 100,AMIN,DMIN
   PRINT 100,AAVG,DAVG
   END
```

```
      SUBROUTINE ORDER(DA,SA,DB,SB,DC,SC,DMAX,SMAX,DMIN,SMIN,DAVG,SAVG)
      DIMENSION S(3),D(3),Q(2),P(2)
      D(1)=DA
      S(1)=SA
      D(2)=DB
      S(2)=SB
      D(3)=DC
      S(3)=SC
      IF(D(3)-D(1))11,11,12
   11 Q(1)=D(1)
      P(1)=S(1)
      Q(2)=D(3)
      P(2)=S(3)
      GO TO 13
   12 Q(1)=D(3)
```

```
   P(1)=S(3)
   Q(2)=D(1)
   P(2)=S(1)
13 IF(Q(1)-D(2))14,14,15
14 DMAX=D(2)
   SMAX=S(2)
   DMIN=Q(2)
   SMIN=P(2)
   GO TO 18
15 DMAX=Q(1)
   SMAX=P(1)
   IF(D(2)-Q(2))16,16,17
16 DMIN=D(2)
   SMIN=S(2)
   GO TO 18
17 DMIN=Q(2)
   SMIN=P(2)
18 CALL VSUM(S(1),S(2),D(1),D(2),DS,SS)
```

```
CALL VSUM(SS,S(3),DS,D(3),DS,SET)
DRAVG=DS/3.
RETURN
END
```

```
      SUBROUTINE VSUM(AB,AA,VB,VA,VR,AR)
      RAD=.0174533
      DEG=57.29578
      AB=AB*RAD
      AA=AA*RAD
    1 BETA=AB-AA
      ALPHA=BETA
      AC=0
      AD=AC-ALPHA
      IF(AD)2,4,25
    2 AD=(360.*RAD)+AD
      ALPHA=AD
   25 IF(ALPHA-(180.*RAD))3,5,3
    3 VB=VB+VA*COS(ALPHA)
      VA=VA*SIN(ALPHA)
```

```
      VVM=(VB**2+VA**2)**.5
      ALPHA=ATAN(VA/VB)
      ALPHA=ABS(ALPHA)
      IF(VA)13,8,14
   13 AC=AC-ALPHA
      GO TO 8
   14 AC=AC+ALPHA
      GO TO 8
    4 VVM=VB+VA
      GO TO 12
    5 VVM=VB-VA
      IF(VVM)7,6,8
    6 AB=0
      GO TO 10
    7 AB=AA
    8 IF(AB)9,12,10
    9 AB=AB+(360.*RAD)
   10 IF(AB-(360.*RAD))12,11,11
```

```
11 AB=AB-(360.*RAD)
12 VR=ABS(VVM)
   IF(BETA)17,18,19
17 AR=(AB-AC)*DEG
   GO TO 20
18 AR=AB*DEG
   GO TO 20
19 AR=(AB+AC)*DEG
20 IF(AR)15,16,16
15 AR=360.+AR
16 AB=AB*DEG
   AA=AA*DEG
   AR=AR+.00000335
   RETURN
   END
```

APPENDIX E

A Paper:

COMPUTER PRODUCED SYNOPTIC ANALYSES OF SURFACE CURRENTS AND THEIR APPLICATION FOR NAVIGATION

by

W. E. Hubert

Commander, United States Navy

COMPUTER PRODUCED SYNOPTIC ANALYSES OF SURFACE CURRENTS AND THEIR APPLICATION FOR NAVIGATION

by

W. E. HUBERT, CDR USN

U.S. Fleet Numerical Weather Facility

Monterey, California

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ABSTRACT

The available methods for estimation of wind currents, mass transport velocity by waves and permanent flow (thermohaline gradient current) are briefly summerized and a simplified computer approach is outlined.

The computed synoptic surface currents are compared with monthly mean current charts and with surface wind conditions. This analysis indicates that the surface currents are greatly wind-driven. A detailed verification procedure which will use the observed changes in sea surface temperature is outlined.

The use of the synoptic current fields for computation of divergence and convergence and the resulting changes in subsurface thermal structure is described. The relative importance of the synoptic surface currents in ship routing, rescue operations and other practices in reviewed.

1. INTRODUCTION

A number of naval, fisheries and other martime operations require a knowledge of the direction and speed of surface currents, as well as their past and near future behavior. The Fleet Numerical Weather Facility (FNWF) at Monterey, California, became interested in ocean currents primarily because of their importance in Anti-Submarine (ASW) applications.

Large variations have been observed in thermocline depth which cannot be explained by mechanical or convective mixing. These changes exhibit cycles which correspond closely to the evolution of synoptic weather patterns over the ocean. It is quite clear that current atlases cannot be used to predict thermocline depth when considerable change can occur in a period of a few days. What is needed for this particular problem are daily current analyses and prognoses.

Navigators also undoubtedly find that atlases, monthly mean charts and the like frequently do not give an exact enough answer to the question: what is the current at a given point in space and time? The purpose of this paper is to report on an attempt to compute surface current flow on a quasi-synoptic schedule and to show some preliminary results. If these results appear to be of use to navigation, means will be found to accomplish dissemination.

2. BACKGROUND

Before selecting and justifying an approach which would be simple but still give some hope of yielding useful results, it was necessary to screen and evaluate a voluminous amount of literature on the subject. Fortunately, a great part of this review had been done recently by Laevastu (1962).

Most theoretical approaches have been mainly concerned with explaining the general, more permanent features of the horizontal circulation patterns (see, e.g., Robinson 1963). The Russians have recently applied correlation theory in an attempt to forecast detailed current changes from a known field; however, our knowledge of the initial state (and particularly its derivatives) is often rather sketchy. Actually, the ocean responds quite rapidly to hourly and daily changes in driving forces, and currents are known to be variable in space and time (Knauss 1960).

These considerations dictated use of a method which would account for fairly rapid response and would stand up to daily verification. Many attempts at current prediction have been disappointments because of oversimplifications resulting from the assumptions made. It seems logical to separate the total current into its elementary components to see which should be neglected, which can be simplified, etc. This is the attack which has been followed in this investigation.

3. COMPONENTS OF SURFACE CURRENTS

Surface currents are caused and influenced simultaneously by a number of forces which vary independently from each other in space and time. If one neglects the special effects due to variation in depth, coastal configuration, runoff, etc., the current vector at a given location, time and depth below the surface (W_{xyzt}) can be given as the resultant of the following components:

$$W_{xyzt} = W_c + W_w + W_i + W_t \qquad (1)$$

where W_c is the permanent flow (thermo-haline gradient current or "characteristic current" as used by Palmen (1930) and Hela (1952)), W_w is the current due to transport by wind and waves, W_i is the periodic part of the inertia current and W_t is the periodic part of the tidal current.

The computations which will be described here cover a period of 24 hours, and it will be assumed that semidiurnal and diurnal tidal components will equal out and can be neglected. In addition, inertial eddies will not be considered because the available quantitative information about their behavior does not warrant their inclusion in this simple technique. The two components which this study will attempt to evaluate are thus the "characteristic" or permanent transport and the transport due to wind and waves.

4. THE CHARACTERISTIC COMPONENT

The characteristic component is directly related to density gradients caused by areal differences in heating-cooling and evaporation-precipitation. Although what we usually call "the permanent flow" is strongly controlled by the large-scale, more-or-less stationary wind systems, only the thermo-haline influences are included in that component here. Wind and wave effects will be lumped into one computation to be discussed later.

Several workers have found (e.g. Yasui 1957) that there is a close correlation between ocean temperature distribution and dynamic depth anomalies. Neglecting salinity, one can apply the well-known meteorological thermal wind relationship in the ocean if one knows the mean temperature of the layer between the surface and some level of zero current velocity. The characteristic current is then given by:

$$W_c = \frac{g\Delta z}{f\bar{T}} \nabla \bar{T} \times \mathbf{K} \qquad (2)$$

where g is gravitational acceleration, f is the Coriolis parameter, $\bar{T}$ is the mean temperature above the level of zero current, ∇z is the depth to zero current, and $\mathbf{K}$ is the unit vertical sector.

The determination of representative mean temperature ($\overline{T}$) is, of course, the critical factor in this part of the problem. The temperature structure of the ocean is certainly not constant, particularly closer to the surface; therefore, semi-synoptic temperature fields should be used if possible. The only place where sufficient data is available for reliable analysis on a daily basis is at the surface so it was decided to use the FNWF Sea Surface Temperature (SST) analyses based on 84 hours of reported ship engine injection temperatures at the top of the layer. In order to include a part of the deeper temperature structure, the SST field is presently combined with a climatological field at 200 meters depth to obtain

$$\overline{T} = K_1 T_{sfc} + K_2 T_{200} \tag{3}$$

Finally, this field is modified empirically in areas where salinity considerations are known to be important (Cyashio, Greenland, Labrador currents). This in effect corrects the ocean temperatures for salinity much as the meterorologist corrects atmospheric temperatures for moisture content when he uses the concept of "virtual temperature."

5. THE WIND COMPONENT

According to Ekman (1906), the direction of the wind current at the surface is 45° to the right of the wind in the Northern Hemisphere and this angle increases with depth. Recent investigations reveal that the deflection is more nearly 12-20 degrees, being larger and more irregular at the lower wind speeds (possibly because of the increased importance of other components) and smaller at higher wind speeds. As the surface wind is about the same angle to the left of the geostrophic wind, it is assumed herein that the direction of the wind current is the direction of the geostrophic wind.

Numerous empirical studies have indicated use of a single factor to relate surface current speed to wind speed. The formula of Witting (1909) appears to agree well with available data and further allows approximate incorporation of mass transport by waves in a simple expression:

$$W_w = K_3 \sqrt{W_g} \qquad (4)$$

where W_g is the mean geostrophic wind speed for a 24-hour period.

In the present work it is assumed that the current is relatively uniform and unidirectional in the turbulent mixed layer down to the thermocline (or about 200 meters). The mass transport of the waves, however, would modify this picture as it decreases exponentially with depth (Masch 1962). Therefore, if W_g is in meters/sec and

W_W in cm/sec, K_3 is taken to be 3.3 for surface currents (ship routing and drift computations) and 2.2 for the average current down to the thermocline (convergence/divergence computations). Obviously, there is a time lag between the change of the wind and response of the sea. This lag seems to be shorter than previously believed, however, and is partially minimized by the 24-hour averaging.

Since all computations are carried out in the standard FNWF grid system, u and v current components are determined at approximately 200 nautical mile intervals for all Northern Hemisphere ocean areas. From these components, direction and total transport (nm/day) fields are determined and stored on magnetic tape for later output in chart form or as special messages giving the currents at specified latitude/longitude intersections.

6. RESULTS

Figure 1 is a hand analysis of one of the first current computations made on a synoptic schedule (18 GMT 16 November 1964). The contours represent total current transport in nautical miles per day; direction arrows have been plotted in the most significant current systems. One can clearly distinguish such well-known features as the Gulf Stream, Sargasso Sea, Labrador Current, Kuroshio and Cyashio. The low-latitude, westerly return flow which results primarily from the "wind component" term is well defined in both the Atlantic and Pacific. A narrow equatorial countercurrent was obtained as a result

of the 200-meter temperature structure used in the characteristic component.

Figures 2a and b are synoptic current charts for the Pacific and Atlantic, respectively, which have been drawn automatically on an incremental x-y curveplotter. Each chart requires approximately one minute to complete and is of sufficient quality that it can be used immediately for radio-facsimile transmission.

Figure 3 is a climatological current chart for winter. It can be seen that many of the most important features are correctly depicted in this approach both in location and intensity.

The problem of automatic plotting of direction arrows on these charts has not yet been solved. However, a possible substitute has been found and is now being programmed for numerical testing. Since u and v current components are available in field form at all grid points, it is believed a stream function field can be determined by a relaxation solution of the Poisson equation

$$\nabla^2\psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad (5)$$

This would permit plotting of a second set of lines (ψ) which would everywhere parallel the direction of flow.

7. VERIFICATION

A synoptic current chart would be of little value if it could not be verified and the computational scheme tuned as required. Direct

current measurements in the open ocean are too few and drift calculations made from navigational fixes are frequently inaccurate in weak current areas, so it is difficult to make a direct evaluation. It has been necessary, therefore, to resort to indirect means which are susceptible to verification on a synoptic basis.

Sea surface temperature (SST) is the only oceanographic element which permits a reasonable complete synoptic analysis on a hemispheric scale. Such analyses are made twice daily at FNWF Monterey (Wolff 1964), and their resolution is such that SST temperature changes can be determined for periods of 24, 48 hours, etc. From these changes will be subtracted the local changes computed from air/sea heat exchange equations. If the remainder correlates well with the advective change indicated by $W_{xyzt} \cdot \nabla SST$, the computed currents can be assumed to be reasonably correct.

This method of verification is now being programmed and numerical results are not yet available. Subjective study of SST change charts and corresponding current charts does, however, indicate that the approach described here is useful. It is evident that the wind component term predominates in many areas, and that it is this term which is mainly responsible for the rapid response of sea surface temperature changes in the ocean.

There are a number of modifications which must undoubtedly be made to this program; it is hoped these will be uncovered during the verification period. One obvious question is - what

effect does thermocline depth itself have upon the surface current speeds above the thermocline?

8. APPLICATIONS

The surface current program was initiated primarily to determine divergence and convergence and the accompanying up and down movement of thermocline depth. Furthermore, the results will be used for forecasting the advective part of sea surface temperature changes.

Over large parts of the oceans the currents have little direct effect on navigation. In some areas, however, they should be taken into consideration in Optimum Ship Routing. Charts of this type should also prove useful in the prediction of ice movement and in any rescue operations.

It is planned to make these computations on a daily synoptic schedule (probably to 06 and 18 GMT), and they could be transmitted from Fleet Weather Centrals in either facsimile or special message format if such is desired. Groups such as the Institute of Navigation may determine that there are applications in navigation which could make use of these products.

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APPENDIX F.

SURFACE DRIFT ELLIPSE PROGRAM

The Surface Drift Ellipse Program which comprises this Appendix was developed by Donald A. Burns of the U. S. Naval Oceanographic Office. The specific instructions for using this program may be obtained by writing to Mr. Burns, Code 3800, U. S. Naval Oceanographic Office, Washington, D. C., 20390. The basic logic of this type of program may be found in _A Statistical Rose Program_, _SP-64_, available from the Evaluation Branch, Oceanographic Analysis Division, Marine Sciences Department, U. S. Naval Oceanographic Office, Washington, D. C.

```
JOB  BURNS OS 53310
FOR
C  SURFACE CURRENT, DON BURNS, O.S.53310, TIDES AND CURRENTS
32766 FORMAT(55HSURFACE CURRENT,DON BURNS,O.S.53310, TIDES AND CURRENTS)
      TYPE 32766
      WRITE OUTPUT TAPE 3,32766
      DIMENSION FREQ(8,6) , SUMV(8),SUMSQ(8), CONST(6), C2NST(6),STA(6)
  100 FORMAT(6A5,5X,6F5.2)
  200 FORMAT(6A5,5X,F6.0)
  300 FORMAT(4X,6F6.0,4X,6F6.0)
  500 FORMAT(6F12.3)
    1 READ INPUT TAPE 5,100,(STA(I),I=1,6),(CONST(J),J=1,6)
      WRITE OUTPUT TAPE 3,100,(STA(I),I=1,6),(CONST(J),J=1,6)
      DO 2 J=1,6
    2 C2NST(J)=CONST(J)**2
```

```
   3 READ INPUT TAPE 5,200,(STA(I),I=1,6),TFREQ
     WRITE OUTPUT TAPE 3,200,(STA(I),I=1,6),TFREQ
     I=1
     IF(TFREQ) 99,99,4
   4 IF(I-7) 5,5,6
   5 K=I+1
     READ INPUT TAPE 5,300,(FREQ(I,J),J=1,6),(FREQ(K  ,J),J=1,6)
     I=I+2
     GO TO 4
   6 DO 106 I=1,8
     SUMV(I)=0.0
     SUMSQ(I)=0.0
     DO 106J=1,6
     SUMV(I)=SUMV(I)+CONST(J)*FREQ(I,J)
 106 SUMSQ(I)=SUMSQ(I)+C2NST(J)*FREQ(I,J)
     TOTAL=0.0
     DO 3000 J=1,8
3000 TOTAL=TOTAL+SUMV(J)
```

```
      DO7 I=1,4
      SUMV(I)=SUMV(I)-SUMV(I+4)
    7 SUMSQ(I)=SUMSQ(I)+SUMSQ(I+4)
      TFREQ=1.0/TFREQ
      XMEAN=TFREQ*TOTAL
      VX=TFREQ*(SUMV(3)+0.70711*(SUMV(2)+SUMV(4)))
      VY=TFREQ*(SUMV(1)+0.70711*(SUMV(2)-SUMV(4)))
      DON=0.5*(SUMSQ(2)+SUMSQ(4))
      VX2=TFREQ*(SUMSQ(3)+DON)-VX**2
      VY2=TFREQ*(SUMSQ(1)+DON)-VY**2
      COV=TFREQ*(SUMSQ(2)-SUMSQ(4))-2.0*VX*VY
      VAR1=VX2+VY2
      VAR2=VX2-VY2
      VAR3=SQRTF(VAR2**2+COV**2)
      EASQ=0.5*(VAR1+VAR3)
      EA=SQRTF(EASQ)
      EB=SQRTF(VAR1-EASQ)
      IF(VAR2) 61,62,63
```

```
   63 E1=EA
      E2=EB
      GO TO 64
   62 E1=EA
      E2=EB
      IF(COV) 161,161,162
  161 THETA=-45.0
      GO TO 65
  162 THETA = 45.0
      GO TO 65
   61 E1=EB
      E2=EA
   64 THETA = 28.6478*ATANF(COV/VAR2)
   65 WRITE OUTPUT TAPE 3,500, XMEAN,VX,VY,THETA,E1,E2
      GO TO 3
   99 WRITE OUTPUT TAPE 3,32767
32767 FORMAT(27H THIS IS THE END OF THE JOB)
      END FILE 3
```

```
TYPE 32767
STOP
END
```

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Development of a computer program for de
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